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Implementation of Unmanned Aerial System-Based (UAS) Digital Photogrammetry for Design, Risk Analysis, and Hazard Mitigation of Rock Slopes

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FINAL REPORT

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ABSTRACT

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INTRODUCTION

The Virginia Department of Transportation is responsible for designing new rock slopes and managing the safety of an unknown number of older rock cuts. There are currently no state-wide inventories of rock slopes in Virginia; however, a rough estimate suggests that there are 1,200 linear miles of rock cuts in the Commonwealth.

In the context of rock slope engineering, the term *design* refers specifically to the process of mapping the orientations and locations of natural structural variations within the rock mass, then using that information to design configurations for the final rock cut. Configurations include determining the steepness and alignment of final rock faces, the placement of artificial support if needed, the inclusion of benched areas, and much more. The intent of rock slope design is to arrive at the safest and most cost effective slope configuration by taking advantage of detailed knowledge of favorable and unfavorable aspects of each rock slope's unique rock structure.

As outlined in the Research Needs Statement, there is a need to determine whether the use of unmanned aerial vehicles, incorporating digital photogrammetry and point-cloud data analysis software, can provide data for rock slope design and rock slope remediation recommendations of a quality comparable to existing traditional ground-based methods incorporating handheld transit compasses and measuring tapes in a manner that offers cost benefits and safety improvements to personnel, the traveling public, and infrastructure.

Key to this is recognizing that rock slopes are not homogeneous isotropic materials, as manmade concrete and steel are assumed to be. In fact, somewhat like the grain in wood, rock masses contain internal variations in texture and structure caused by various natural processes acting over time. To truly evaluate the safety and stability of highway rock slopes, those geologic variations must be mapped and documented carefully so that their impacts on stability may be planned for in the design and remediation of rock cuts. If a simple rule-of-thumb, cookie-cutter, approach to shaping highway rock cuts worked consistently, agencies today would not be faced with unstable rock cuts.

Rock slope stability is controlled by the presence and orientations of geologic structures called discontinuities. Discontinuities are breaks in the continuity of a rock mass. Detachment and sliding occur along discontinuities and they also serve as conduits for water. These factors readily contribute to the increased likelihood of hazardous rockslides and rockfalls. Geologic discontinuities include bedding planes in sedimentary rock, foliation planes in metamorphic rock, and tectonic joint sets in all types of rock, along with individual fractures and fault zones.

Of greatest importance to stability analyses for slope design and remediation is mapping the locations and orientations of weak discontinuities with respect to actual or proposed rock slope faces. Unmanned aerial vehicles (UAVs) and unmanned aerial systems (UASs) enable safer remote collection of geologic structure data at dangerous sites. This is accomplished by flying above or adjacent to sites to capture video, still imagery, and sometimes LiDAR point clouds from perspectives not otherwise available. In contrast, traditional data collection techniques require extensive time-consuming fieldwork, often in dangerous terrain; exposure to rockfall; mountaineering skills for climbing on or rappelling down slopes; and engineering geologic field data collection skills.

The accuracy of geologic measurements for rock slope design purposes using accepted traditional handheld transit compasses and tape measures is plus or minus 2-degrees of angle and 0.5 ft in distance. The results of this study confirm that geologic data extracted from 3D virtual slope models generated from UAS imagery are of that same or greater quality, and they are collected in greater quantities, with improved safety, efficiency, and cost savings over traditional methods.

Applications of UAS data not critical to design of rock slopes were also explored. Those included change detection for monitoring slope movements, the generation of orthomosaic maps, and quantity estimates such as square footage of applied protective rockfall mesh.

PURPOSE AND SCOPE

Purpose

The purpose of this research has been to determine whether the deployment of unmanned aerial vehicles (UAVs) or unmanned aerial systems (UASs) with additional autonomous flight capabilities, would result in rock slope design and rock slope remediation recommendations of a quality comparable to, or better than, existing traditional and ground-based methods, in a manner which offers cost benefits and safety improvements to personnel, the traveling public, and infrastructure.

The specific objectives defined and approved for this research are:

1. Establish the methods, protocols, and workflow for safely using UAS for rock slope stability investigations along highways in accordance with federal, state, and local laws;
2. Test the accuracy of UAS mapping for these specific rock slope applications using ground control points and least squares analysis;
3. Provide software recommendations and establish the workflow for extracting the geologic structure data needed for characterizing rock slopes to aid in slope design, remediation, and hazard inventories, from UAS 3D computer models;
4. Establish the workflow for using UAS point clouds for modeling of rockfalls using 3D applications like the Colorado Rockfall Simulation Program (CRSP), in collaboration with the Federal Highway Administration (FHWA); and,
5. Test the use of change detection software for detecting slope changes over time from 3D UAS digital models for at least one slope.

Scope

Site Selection

Seven sites, consisting of six highway cuts and a limestone quarry, were chosen for meeting the objectives by testing the suitability of UAS for rock slope data collection under a wide variety of conditions. Three more sites were chosen than originally proposed. The additional sites were selected to provide a broader range of conditions tied to the severity of rock slope hazard, operational work space, traffic volume, and safety for all concerned, in order to better address the specific objectives above. Some sites are suitable for achieving all five listed objectives, while some objectives could be achieved at only one or two sites, due to site characteristics and timing of visits.

Locations

Figure 1 shows the locations of all selected sites, spread across the Commonwealth of Virginia. Four are in the Valley and Ridge geologic province, two are in the Blue Ridge geologic province, and one is shown within the Piedmont geologic province. That is the Lynchburg site which in reality lies on the eastern limb of the Blue Ridge Anticlinorium, hence technically is part of the Blue Ridge geologic province. Three of the sites are located on interstate highways while three are located on state routes. The remaining data collection site is in the Salem Stone ACCO Quarry, adjacent to the Smart Road test bed, near Blacksburg. The Salem Stone Holston Quarry, near Dublin, was used as an aircraft flight testing area.

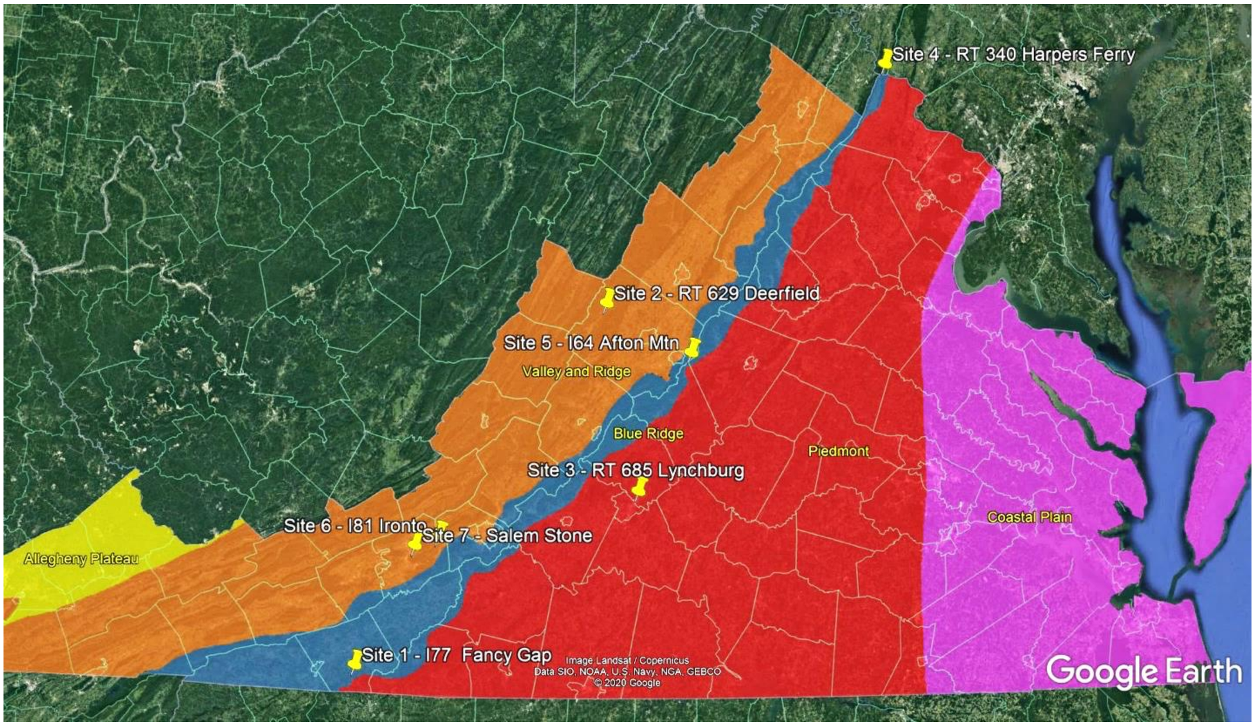

Figure 1. Map of site locations for testing the implementation of UAS digital photogrammetry for rock slope safety mitigation and design. From west to east, the colored Geologic Provinces are the Allegheny Plateau, Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain in a greatly simplified map.

METHODS

Overview

This study called for achieving the five objectives, by completing the thirteen tasks below, distributed across seven different sites. Sites were selected to provide a variety of conditions needed for meeting the five objectives. Not all tasks were performed at each site.

Tasks

1. *Select six highway sites and one quarry site for a total of seven test sites*
2. *Establish site safety plans*
3. *Establish and test ground control points (GCPs) for at least one site*
4. *Obtain traditional geologic structure mapping data*
5. *Retain mountaineering consultants to oversee safe rope access*
6. *Analyze traditionally-collected data for design and mitigation purposes*
7. *Fly the sites with UAS to collect aerial imagery*
8. *Process UAS imagery for configuration design and mitigation purposes*
9. *Perform 3D rockfall simulations*
10. *Compare traditional ground-based results with UAS results*
11. *Test change detection software for slope monitoring*
12. *Evaluate cost-benefit and risk-reward results*
13. *Share results with stakeholders and implement best practices*

Methods for Each Task

Tasks

Task 1 - Select six highway sites and one quarry site for a total of seven sites

Six highway test sites, a quarry site, and a separate quarry just for flight testing, were selected as research locations. Among other considerations, this task required a review of the geologic characteristics of each proposed site. The sites exhibit diverse environmental and geologic conditions, typical of highway corridors in Virginia where rockfall and rockslide hazards are known to exist. Also considered were site characteristics related to suitability for achieving the stated objectives. Site locations are shown in Figure 1.

Task 2 - Establish site safety plans

A general safety plan was established for this research that included provisions for overall site safety, safe maintenance of traffic (MOT), UAS operational safety, and safety briefings for all on-site personnel. The general safety plan served as the guide for establishing individual safety plans to fit the unique needs of each site.

Task 3 - Establish and test ground control points (GCPs) at selected sites

Ground control points (GCPs) were established at three of the seven sites in order to meet Objective 2. Those sites were #2 Deerfield, #4 Harpers Ferry, and #5 Afton Mountain. GCPs are survey-grade reference points used to tie a point cloud, and its derivate products, such as topographic maps and orthophoto mosaics, most accurately to real world coordinate systems. Structure-from-motion software, such as *Pix4D Mapper*, utilizes manual tie points (MTPs) to adjust and improve the precision of a points within the cloud's unique coordinate system. MTPs that are assigned survey grade coordinates become GCPs, and are utilized to adjust and improve the accuracy of the point cloud within real world coordinate systems. That real-world accuracy can be tested using root mean square (RMS) analysis, as shown in the results section. For this research, GCPs were surveyed using an Emlid Reach (fixed base GPS station) and an Emlid Reach real time kinetic (RTK) rover unit. RMS analysis was performed only for the #2 Deerfield site.

Task 4 - Obtain traditional geologic structure mapping data

Two sites (#2 Deerfield and #5 Afton Mountain) were mapped geologically using traditional data collection techniques typical for detailed rock slope stability analyses. Rock mass discontinuity orientation data were obtained using transit compasses and smart device applications. Historic data were also available for comparison and inclusion in the analyses.

Task 5 - Retain mountaineering consultants

The complete and thorough collection of data manually requires access to the rock face using mountaineering techniques. Certified climbing consultants were to be hired to train and certify faculty-student teams to ensure safety on the slopes. As circumstances prevented this, previously-trained faculty and a student were used for manual data collection. Historic data were available from past studies and also used, as described above.

Task 6 - Analyze traditionally collected data for design and mitigation purposes

Geologic structure data collected manually at Deerfield and Afton were analyzed using standard methods to serve as baselines for comparisons with UAS-collected data. Slope stability analyses at each site included both kinematic stereonet evaluation to identify likely modes of failure, and safety factor calculations based on limiting equilibrium equations.

Task 7 - Fly the sites with UAS to collect aerial imagery

The methods used at each site were selected based on site conditions and overall research objectives specific to each site. Sites were flown using aircraft from Radford University's squadron of FAA-registered UAVs. All flights were conducted in compliance with FAA rules and regulations. The available aircraft included models made by DJI, SenseFly, and 3D Robotics. Missions included manual stick-and-rudder flights as well as pre-programmed autonomous flights controlled by various software applications. Flight data and imagery were transferred from aircraft storage cards to external hard drives, as well as secure online sites, in preparation for processing.

Task 8 - Process UAS imagery for design and mitigation purposes

High resolution aerial images collected at each site were processed to create virtual 3D models as point clouds and 3D triangle meshes, also known as triangular irregular networks (TINs). The structure-from-motion (SfM) software package, *Pix4D Mapper*, was used in this study. It was also used to generate orthophoto mosaics and contour maps at selected sites for use as layers in *ESRI ArcGIS* and *GIS Pro* applications. Geologic structure data, needed for design and mitigation analyses, were extracted from digital point clouds using *CloudCompare* and *Split-FX* applications. Discontinuities were plotted on stereonets using *RockPack III* (RockWare, C.F. Watts), and *DIPS* (RocScience).

Task 9 - Perform 3D rockfall simulations

Rockfall simulation modeling is used to predict the travel paths and kinetic energies of rocks that might roll towards roadways. Knowledge of bounce heights and impact forces is fundamental when designing safe slopes or planning rockfall barrier systems. The simulations can be performed in either 2D or 3D and rely on surveyed slope profiles or point cloud models derived from UAS-generated slope geometries or ground-based surveys. Anticipated collaboration with the Federal Highway Administration (FHWA) fell through. Nevertheless, 3D models suitable for performing the rockfall simulations were generated and are now available for future use.

Task 10 - Compare traditional ground-based results with UAS results

Site #2, Deerfield, was used for an exhaustive comparison of traditional ground-based methods and UAS-based methods for collecting the geologic structure data needed for the design and mitigation of rock slopes. Discontinuity orientation values derived from UAS data were plotted on stereonets using industry standard software, and compared to the results from traditional methods plotted in the same manner and described above in Task 6. Comparisons were made using both visual and statistical techniques on stereonet projections.

Task 11 - Test change detection software for slope monitoring

Owing to extensive UAS data available for Site #2, Deerfield, collected between 2016 and 2019, and the ongoing rockfall activity there, Site #2 was chosen as the ideal location for testing change detection applications using aerial imagery. Student researchers flew the site in 2019 as part of this research, generated dense 3D models for their flights and for historic flights from 2016, and registered the two data sets in a common coordinate system. Differences between the two 3D models were color coded revealing rockfall source areas and areas of rockfall accumulation.

Task 12 - Evaluate cost-benefit and risk-reward results

Cost-benefit and risk-reward analyses were attempted by comparing costs associated with data collection by UAS aerial-based techniques to traditional ground-based techniques. Maintenance of traffic (MOT) costs are believed to be among the greatest of expenses, but are outside our expertise. Also considered are cost reductions resulting from the increased efficiency of collecting larger quantities of data through aerial remote sensing methods compared to traditional mapping, often requiring rope access skills. The benefits of increased safety are of paramount concern, as related to both the traveling public and to worker safety during UAS-based investigations compared to ground-based investigations. These costs are difficult to estimate and should constitute separate study.

Task 13 - Share results with stakeholders and implement best practices

This research is generating keen interest from various stakeholder groups. Results and recommendations for implementing best practices are presented not only in this report, but will also be shared at professional meetings, conferences, workshops, and short courses. Research findings have been requested by the Rockfall Subcommittee of the Engineering Geology Committee of the Transportation Research Board. A manuscript by graduate student Rachael Delaney, based on preliminary results, has been accepted for publication in the journal *Environmental and Engineering Geology* (Delaney, et al., 2020). Results from this site have been incorporated by HDR and GeoStabilization International for projects at Sites #4 and #6.

RESULTS AND DISCUSSION

This section summarizes results for the thirteen tasks identified to meet the five research objectives. All thirteen tasks were addressed at one or more sites during this research. Not all locations were suitable for all tasks.

Task 1 - Select six highway sites and one quarry site for a total of seven sites

Introduction - Sites Selected

1. UAS Test Site #1 - Interstate 77, Multiple Mileposts, Fancy Gap Mountain, Virginia
2. UAS Test Site #2 - Route 629, Deerfield, Virginia
3. UAS Test Site #3 - Route 685, River Road, Lynchburg, Virginia
4. UAS Test Site #4 - Route 340, Harpers Ferry, Virginia
5. UAS Test Site #5 - Interstate 64 Milepost 101 WB, Afton Mountain, Virginia
6. UAS Test Site #6 - Interstate 81 Milepost 126.7 SB, Ironto, Virginia

7. UAS Test Site #7 - Salem Stone, ACCO Quarry, Blacksburg, Virginia, and Holston Quarry, Dublin, Virginia

Site Selection Criteria

A critical aspect of site selection includes evaluating and understanding how the regional, local, and site geology impact the safety and stability of road cuts in mountainous terrain.

The geologic setting includes the ages and types of rocks present, rock mass condition, and the types and orientations of planes of weakness within the rock mass called discontinuities. Discontinuities are breaks in the continuity of the rock mass along which water might easily flow, and along which sliding and detachment might occur, resulting in rockslides and rockfalls.

The seven sites selected for this research are geologically diverse, situated in the Blue Ridge and Valley and Ridge geologic provinces of Virginia. The region is characterized by folded and faulted rock strata. The resulting geologic structures, especially discontinuities, nearly always control the stability of rock slopes in competent rock. Sites were selected on the basis of geologic conditions favorable to rockfalls and rockslides in a variety of roadway settings.

Site #1 Description - Interstate 77, Multiple Mileposts, Fancy Gap Mountain, Virginia

Site #1 (Figure 2) consists of three rock slope work zones close to each other, south of Fancy Gap on I-77. The specific locations are MP 5.4 SB, MP 3.8 SB and MP 3.7 NB. In 1989, Dr. Watts documented rockfalls that blocked lanes and caused detours for over a week at MP 5.4 SB.

The dominant rock type at the Site #1 locations is garnet-muscovite-biotite gneiss of the Alligator Back Formation. The rock is characterized by a fine “pin-striped” appearance, due to transposed thin compositional layers or laminations (Rankin et al., 1973). Multiple episodes of ductile deformation produced refolded tight to isoclinal folds and a penetrative metamorphic foliation. The contact with the underlying Ashe Formation was originally considered stratigraphic (Rankin et al., 1973), but more recently has been recognized as a zone of high strain (Carter et al., 2017). The ages of the Ashe and Alligator Back Formations are uncertain, but commonly presumed to be Neoproterozoic (Z) to Lower Paleozoic (Carter et al., 2017). The rocks are strongly jointed, and steeply southeast-dipping joint sets or foliation planes dominate stability at the site locations.

Figure 2. UAS photograph of Site #1 work area on I-77 at MP 5.4 southbound, looking north. Foreground shows slope after rock scaling in preparation for treatment with rockfall protection mesh. Distant slope is awaiting treatment.

Site #2 Description - Route 629, Deerfield, Virginia

Site #2 (Figure 3) is located on Route 629 in the Valley and Ridge province, in Augusta County near Deerfield, Virginia. It has a history of both major and minor rock slope failures. The most serious occurred in May 2009 when a large rock mass slid along bedding planes and blocked both of the travel lanes.

Figure 3. UAS photograph of Site #2 Route 629, Deerfield. Center right shows recent slope failure threatening anchor block for guy wires (hard to see) supporting transmission line tower out of sight.

The cut slope at Site #2 consists of dark gray shale belonging to the Brallier Formation of Devonian age. The shale is interbedded with siltstone and minor micaceous sandstone (Rader and Wilkes, 2001). The strata are folded around the axes of a paired anticline-syncline (Neiman, 2013). The most obvious discontinuities present at the site are bedding planes dipping roughly 25° to 35° towards the southeast and near-vertical orthogonal joints dipping to the northeast and northwest. The beds range in thickness from 2 in (5 cm) to 6 in (15 cm) and are heavily jointed. Discontinuities are generally tight and smooth-surfaced, although a few have an aperture > 0.4 in (1 cm).

The bedding planes that dip steeply to the southeast tend to dominate stability at this location. The southbound lane is most directly affected by the unstable portions of the slope on the west side of the road. The east side of the road drops down to the floodplain of the Calfpasture River. Weathering between the sedimentary rock layers over time weakens support between bedding planes allowing rock masses to periodically detach and slide down the bedding plane surfaces.

The upper portion of the slope exhibits an overturned drag fold with a continuous slick slide surface. The hanging wall portion is heavily fractured and continues to shed rock, even as recently as within the past year. These conditions make it an ideal location for 3D modeling, the extraction of structure data for stability analyses, and using change detection software to document and monitor the rock mass.

Site #3 Description - Route 685, River Road, Lynchburg, Virginia

Site #3 (Figure 4) is located on Route 685, River Road, along the north bank of the James River across from downtown Lynchburg. It was suggested for consideration by Lynchburg District Geologist James Hall due to occasional rockfalls onto the shoulder and highway.

Stratigraphically, Site #3 lies within biotite gneiss and interlayered mica schist of the Neoproterozoic (probable) Ashe Formation. In the region, massive conglomeratic schist and gneiss grade upwards into two-mica plagioclase gneiss. Locally, quartzite, impure marble, and amphibolite occur (U.S. Geological Survey, 2020) The Ashe Formation sits unconformably on porphyroblastic augen gneiss of "Grenville" age (~1 by), and is cut by younger mafic and felsic dikes.

Structurally, the rocks lie on the southeastern limb of the Catoctin-Blue Ridge anticlinorium, and specifically within the asymmetric, NW-verging Lynchburg anticline (Brown, 1958). Bedding and compositional layering dip moderately to steeply southeast, and axial planar cleavage and minor folds are common. Slip cleavage related to folding is present in schistose layers (Brown, 1958).

Figure 4. UAS photograph of Site #3, Route 685 River Road Lynchburg. Right side shows large rocky slope face with potential block failures controlled by the structural geology.

Site #4 Description - Route 340, Harpers Ferry, Virginia

Site #4 (Figure 5) is located on a section of Route 340 along the Potomac River, east of the junctions of the Virginia, West Virginia, and Maryland state lines. This location was suggested for inclusion in the study as a test site-of-opportunity, in that HDR had a contract with VDOT to prepare a mitigation feasibility plan for the slope. Stability of the rock here is controlled by the orientations of joint set discontinuities.

In this area, the river cuts through stratigraphic units of the Blue Ridge, including Mesoproterozoic monzogranite unconformably overlain by the Neoproterozoic Swift Run and Catoctin Formations (Southworth and Brezinski, 1996). The monzogranite, which was imaged in this study, is massive, coarse- to medium-grained, leuco-granite containing up to 5% almandine garnet. This rock is intruded by metadiabase dikes composed of actinolite, chlorite, epidote, and albite (Southworth and Brezinski, 1996).

Figure 5. UAS photograph of the east end of Site #4, Route 340 at Harpers Ferry. Center left shows a pod of competent rock where stability is controlled by joint sets. The rock mass changes to softer weathered rock and soil moving to the right (west) causing stability to be controlled by the strength of soil and soft rock.

Site #5 Description - Interstate 64 Milepost 101 WB, Afton Mountain, Virginia

Site #5 (Figure 6) is located on Interstate 64 near Afton Mountain at milepost 101, as the westbound lanes rise up the side of Afton Mountain. Rockfalls and slides, along steeply dipping foliation planes, have been a major problem along this portion of highway for decades.

Afton Mountain is one of a series of linear to arcuate mountain ridges with steep slopes and deeply incised stream valleys that characterize the topography in this portion of the Blue Ridge. The Neoproterozoic Catoctin Formation, which underlies most of Afton Mountain, is ~1500 to 3000 ft (~450-900 m) thick unit composed primarily of very hard, massive to schistose, dark green metabasalt, commonly containing pods of light green epidosite (epidote + quartz) (Badger and Sinha, 2004). Phyllites are especially significant because they weather to friable, paper-thin, sericite and clay-rich layers ("paper shales") that provide excellent potential surfaces of movement.

Numerous planar to gently undulating foliation planes, probably coincident with original bedding, are evident at Site #5. Dip angles are in the 35°-45° range with dip azimuths clustered about 150°. I-64 trends ENE (060°) along here, with a cut slope dip of about 42°. Thus, many of the foliation surfaces daylight directly out of the open cut slope. In addition to the foliation, swarms of joints are present, with generally steep dips (60°-90°) and dip azimuths to the southeast (140°-160°) and southwest (215°-245°). The joints therefore act with bedding to produce wedge failures or provide release surfaces from which rockfalls or slides along the bedding planes can occur (Watts and Whisonant, 1988). Thin (few cm) zones of shaley material are present along some foliation surfaces.

Active water seeps or extensive iron staining representing intermittent seepages occur along foliation and joint surfaces. Calcite mineralization and veins are present along some discontinuities. Veins of a fibrous, asbestos-like mineral are present in the greenstone also. These additional geologic materials must play a significant role in the ongoing rockfalls and slides that occur at this site.

Figure 6. UAS photograph of Site #5, I-64 at MP 101 near Afton Mountain looking westbound. This is the site of previous rockslides; one of the worst occurred in 1989 and blocked the westbound lanes.

Site #6 Description - Interstate 81 Milepost 126.7 SB, Ironto, Virginia

Site #6 (Figure 7) is located on Interstate 81 near Ironto at milepost 126.7 southbound. It was suggested for inclusion in this research by the firms HDR and GSI, as they were in the process of mitigating a landslide there for the Virginia Department of Transportation. A three-mile portion of I-81 here has a significant history of slides controlled by geologic structure.

Occurring in the Valley and Ridge province, this site is underlain by limestone and cherty dolomite of the Cambrian Elbrook Formation. Slaty dolomite, maroon argillite, and pods of tectonic breccia occur locally (Henika, 2010). This location lies southwest of the Roanoke recess, a major bend in the Appalachian trend that demarcates a striking difference in structural style of the Valley and Ridge. Northeast of the bend the dominant structures are regional-scale folds, whereas southwest of the bend thrust faults dominate (McDowell and Schultz, 1990).

Accordingly, Site #6 is in the hanging wall of the Salem thrust sheet, a branch of the Pulaski thrust system. A prominent set of NW-SE plunging, reclined to recumbent folds are perpendicular to the leading edge of the Salem fault, and the site lies within an asymmetric, northwest-plunging syncline. Bedding typically strikes northeast and dips southeast toward the highway, although some beds have been rotated to northwest strike with variable dips (Henika, 2010). Significant structurally controlled landslides have occurred between milepost 128 and 125 because of the bedding and the ramp faults having dips toward the highway.

Figure 7. UAS photograph of Site #6, I-81 at MP 126.5 southbound, looking northbound. The current landslide is adjacent to the trucks placed as temporary rockfall barriers. The site of a massive 1969-70 landslide is at, and rising to the left above, the grassy area just beyond the curve in the distance at about MP 127.0. This picture illustrates the challenging nature of the site for UAS flights: dense leaf-on vegetation, narrow valley, rugged median sloping down toward the northbound lanes.

Site #7 Description - Salem Stone, ACCO Quarry, Blacksburg, Virginia and Holston Quarry, Dublin, Virginia

Site #7 consists of two locations designated Site #7a, used as a data collection site, and #7b, used as an aircraft proving ground. Wedge-shaped rock masses formed by bedding-joint intersections, as well as localized faulting, causes slope instability at Site #7a and in the adjacent rock cut for the Virginia Tech Transportation Institute's (VTTI) Smart Road (Reed, 2003).

Both sites are quarries owned by Salem Stone Company. Site #7a is located adjacent to the Smart Road near Blacksburg and referred to as the Salem Stone ACCO Quarry. The site was originally chosen as a good location for evaluating change detection applications, using UAS imagery collected between production blasts. Uncertain blasting schedules led to Site #2 Deerfield being used for that purpose.

Site #7b (Figure 8) was a test range for evaluating different drones, mission planning software, and the use of drone-borne LiDAR in a quarry setting. Referred to as the Salem Stone Holston Quarry, it is adjacent to I-81at Exit 101. It was also the crash site for the heavy-lift UAV carrying Radford University's LiDAR unit. The incident caused irreparable damage to the unit.

The geologic setting of the primary location, Site #7a, is underlain by deformed carbonate rocks displaced by the Salem thrust fault. The dominant rock unit at this site is the upper Cambrian Copper Ridge Formation, consisting dominantly of dolostone with minor silty and sandy zones (Reed, 2003). Bedding typically dips E-SE, with dip angles of 23° to 45°. In addition to bedding, repetitive, steeply to shallowly dipping joint discontinuities are prominent. Both types of surfaces are planar, and commonly covered by a thin clay-like coating. Some bedding surfaces also display a white, powdery substance formed by authigenic zeolites.

Figure 8. UAS Mavic Pro photograph of Site #7b, the Salem Stone, Holston Quarry, near Dublin. This was used as a flight-testing area and was the location of the crash that took the LiDAR unit out of service for the remainder of the research study. Graduate student James Young (center) is preparing to launch the DJI Matrice 600 (inset) with LiDAR mounted.

Task 2 - Establish site safety plans for each site

Introduction

Site safety plans for UAS were established for this research and separated into three components:

(1) Construction Site Safety
(2) FAA UAS Regulations and Local Safety
(3) Flight Operations and Best Practices

(1) Construction Site Safety

a) If an active construction site, attend safety brief by foreman, or foreman's representative, for all on-site personnel, including sites with measures for maintenance of traffic (MOT) already in place.
b) Attend pre-flight brief by the FAA-certified remote pilot in command (RPIC) for all on-site personnel. Brief covers mission objectives, flight paths, expected aircraft behavior, and emergency procedures such in case of as loss-of-signal
c) If the site is an area of interest or concern with normal traffic flow, the following applies:
    i. Work with transportation districts to set up MOT and warning signage for shoulder or lane closure, if needed; or,

        ii. Establish a temporary mobile work zone using high visibility vehicles with strobe warning beacons, cones, and signs located up-traffic from the work area.

d) Take all reasonable precautions to avoid distracting motorists with the aircraft:
    i. Use work vehicles to block views of take-off and landing locations; or,
    ii. Take off and land behind barriers or far away from travel lanes and fly into the target area from above;
    iii. Do not fly lower than 40 feet adjacent to the highway to minimize distractions;
    iv. Use visual observers (VOs) strategically placed with radio contact at all times.

(2) FAA UAS Regulations and Local Safety

a) FAA-certified remote pilot in command is required.
b) Obey all FAA rules pursuant to Part 107 regulations.
c) Request FAA flight authorizations for the location, date, and time using the online LAANC (Low Altitude Authorization and Notification Capability) system.
d) Identify and notify local stakeholders including the DOT, law enforcement, municipalities, and property owners.

(3) Flight Operations and Best Practices

a) Maintain all aircraft systems, batteries, propellers, etc., in accordance with manufacturer's specifications.
b) Keep all aircraft firmware and flight control applications up-to-date.
c) Conduct regular practice / training flights, to include manual and autonomous missions.
d) Always test aircraft and systems after any system changes, including upgrades to firmware, updates to flight control applications, incorporating any new flight control software, and deploying any new aircraft even the UAV operator has experience with that model.
e) Review and be fully aware of aircraft settings, especially those for emergency procedures including:
    i. Loss of signal contact with remoter controller;
    ii. Loss of contact with flight control application;
    iii. Critically low battery during flight;
    iv. Receiving "return to launch/home" command;
    v. Receiving "land now" command.
f) Plan mission strategies in advance of arriving on site for both manual and autonomous missions including:
    i. Use satellite imagery, available maps, and other imagery to visualize safe flight paths;
    ii. Plan for reconnaissance contingency flight(s), to capture revealing site video(s) from alternate perspectives and to identify obstacle locations and heights;
    iii. Prepare autonomous flights in advance using mission planning software and save the mission with its base maps to prevent mission failures in cases of no Internet availability;
    iv. Review flight plans for safety and for meeting mission objectives by at least two personnel including the FAA-certified RPIC.

Task 3 - Establish and test ground control points (GCPs) at selected sites

Ground control points (GCPs) were established at three of the seven sites to meet Objective 2. Those sites were: Site #2 Deerfield, Site #4 Harpers Ferry, and Site #6 Afton Mountain. For brevity, only the results from Deerfield are provided here. GCPs are survey-grade reference points used to tie a UAS point cloud, and its derivative products, such as topographic and orthomosaic maps, most accurately to the real world. For this research, GCPs were established using an Emlid Reach fixed base station and a real time kinetic (RTK) rover survey unit, shown in the Figure 9 inset.

Route 629, Deerfield, Virginia

For the Deerfield site, geospatial sciences graduate student, James Young performed a test of UAS point cloud positional accuracy using root mean square analysis (Figure 9). Table 1 shows the results when compared to surveyed RTK checkpoints. The mean RMS error, with respect to georeferencing, was found to be 0.176m (0.575ft) during image processing using *Pix4D Mapper* software. Resolving that offset vector into its three X, Y, and Z components (east-west, north-south, and vertical), the root mean square (RMS) errors were found to be 0.179256m, 0.3366262m, and 0.099307m (0.5881ft, 1.1044ft, and 0.3258ft) respectively (Table 2). Similar values are anticipated for flights at Site #4 Harpers Ferry and Site #5 Afton Mountain. While not considered accurate enough for highway design, these results are superior to traditional transit compass and tape measurements currently used for ground-based collection of geologic structure data.

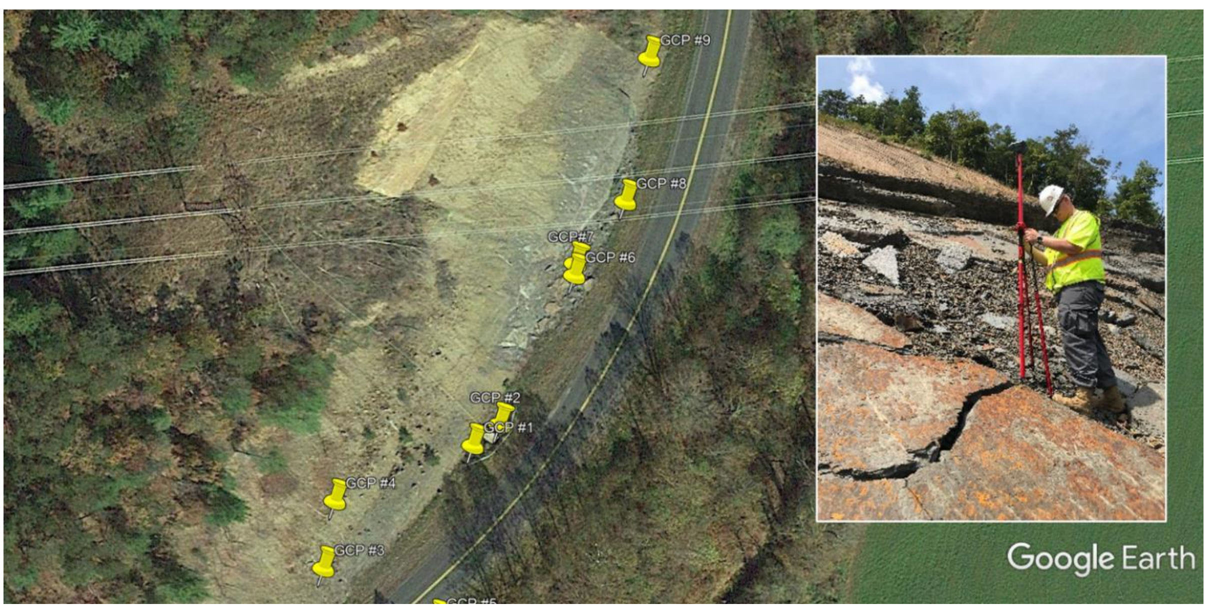

Figure 9. Satellite image of surveyed ground control points (GCPs) at Site #2 Deerfield. The inset shows graduate student James Young obtaining coordinates for GCP #7 using a roving, Emlid RTK GPS receiver, synchronized to a nearby base station in 2019. Base map from Google Earth.

Table 1. *Pix4D Mapper* image processing parameters and results, including overall georeferencing accuracy for a Deerfield flight, compared to surveyed ground control points (GCPs), in terms of RMS Error. Errors were calculated in *Pix4D Mapper* by comparing points in the 3D models identified with GPS coordinates obtained directly from the aircraft, without correction, to select surveyed GCPs from the map locations shown above in Figure 9.

? **Images**	median of 39125 keypoints per image	✓
? **Dataset**	281 out of 281 images calibrated (100%), all images enabled	✓
? **Camera Optimization**	3.19% relative difference between initial and optimized internal camera parameters	✓
? **Matching**	median of 21625 matches per calibrated image	✓
? **Georeferencing**	yes, 3 GCPs (3 3D), mean RMS error = 0.176 m	⚠

Table 2. UAS mapping accuracy in X, Y, Z directions (east-west, north-south, and vertical vectors) for the Deerfield site in terms of root mean square (RMS) error. RMS values were calculated using the *Pix4D Mapper* program by comparing points in the *Pix4D* 3D models, generated using GPS coordinates obtained directly from the aircraft, to select surveyed GCPs.

GCP Name	Accuracy XY/Z [m]	Error X [m]	Error Y [m]	Error Z [m]	Projection Error [pixel]	Verified/Marked
GCP1 (3D)	0.010/ 0.020	-0.061	-0.058	-0.042	2.608	6 / 6
GCP2 (3D)	0.004/ 0.020	0.303	0.579	0.166	0.278	20 / 20
GCP3 (3D)	0.008/ 0.020	0.029	0.006	0.017	1.913	8 / 8
Mean [m]		0.090545	0.175555	0.047097		
Sigma [m]		0.154707	0.286785	0.087429		
RMS Error [m]		0.179256	0.336252	0.099307		

Task 4 - Obtain traditional geologic structure mapping data

Data from traditional geologic mapping surveys were obtained for all sites. Some discontinuity orientation measurements were included in the collection process as part of standard operating procedures. However, detailed structure mapping of the type needed for rock slope stability analyses and mitigation were specifically obtained for two sites: #5, Afton Mountain, and #2, Deerfield. The Afton Mountain structure data are historic, coming from a Radford University - VDOT stability investigation in 1987-88 (Watts and Whisonant, 1988). On the other hand, the Deerfield data are more recent, collected as part of ongoing Radford University stability studies and as part of this study.

Geologic Structure Mapping:

Geologic mapping consists of documenting features including the rock types that are present, specific lithologies and sequences, overall rock mass strength characteristics, and typically over 100 measurements of the orientations and characteristics of weaknesses in the rock mass known as discontinuities. Discontinuities are breaks in the continuity of the rock mass along which water can flow more easily, than through the rock, and along which sliding and detachment can occur resulting in rockslides and rockfalls.

Orientations of discontinuities are critical since those that dip toward highways are the dominant cause of rockslides and rockfalls, alone or in combination with other discontinuities. Traditionally, rock mass discontinuity orientation data are obtained manually using a transit compass or, more recently, by placing smart devices on the structural surfaces to obtain automatic readings using downloaded applications.

Figure 10 is a map showing discontinuity orientations on numbered stereonets along the I-64 westbound lanes, less than .25 miles west of Site #5. The geologic structures along this portion of the interstate are within the same domain and are consistent with each other. The inset shows former graduate student Robin Reed measuring the dips and dip directions of those discontinuities, using a transit compass, at Afton Mountain in 1987. Additional data were collected manually as part of this VTRC-funded research in 2019.

The irregular closed shapes within the stereonets in Figure 10 represent clusters of discontinuities plotted in the dip vector format. In stereonet #4 (Figure 10), only two clusters are present, one large and one small. If one imagines the circular stereonet as a compass, a larger cluster can be seen in the southeast quadrant and a smaller cluster near the center of the stereonet. When plotted as dip vectors, the closer to the center that a cluster appears, the more steeply dipping the discontinuities represented by it are.

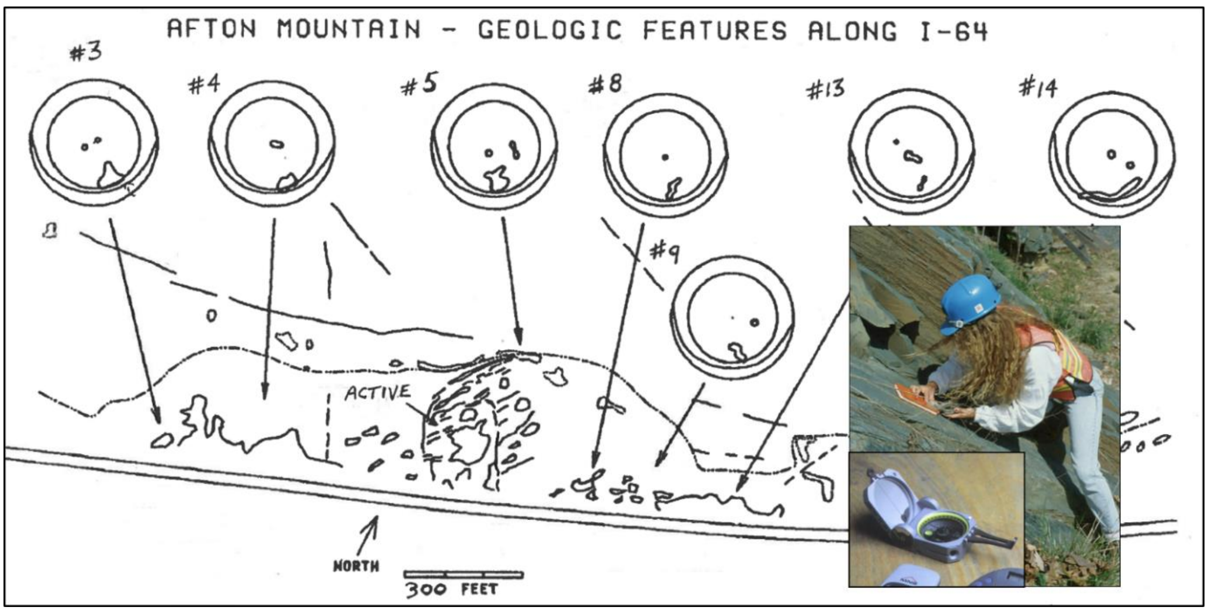

Figure 10. 1988 map of geological features and structural data presented as dip vector stereonets for Site #5, Afton Mountain. The inset shows former graduate student Robin Reed using a transit compass to measure discontinuity orientations at Afton Mountain. This map of *Geologic Features* is from Watts and Whisonant, 1988.

The smaller cluster in stereonet #4 is very steep and so cannot actually daylight out of the slope face. Those discontinuities are steeper than the slope face. Conversely, the closer to the outer circle (the primitive) a cluster of discontinuities is located, the more gently those discontinuities are dipping. They are more likely to dip less steeply than the slope face, hence they are likely to daylight out of the slope face providing surfaces on which sliding can occur.

Task 5 - Retain mountaineering consultants

The goal of this task was to facilitate safe traditional data collection, above road level, by certifying new data collection teams with mountaineering skills to include rock climbing and rappelling. Contract complications eliminated mountaineering consultants as an option for training. Fortunately, Drs. Watts, Sethi, and McClellan, and student Robert Huber, had previous rope access training and were available for on-slope data collection as needed. As a result, those individuals collected rock structure data at Site #2, Deerfield, and Site #5, Afton Mountain. These data were used in conjunction with geologic structure data collected earlier, for traditional-style stability analyses and for comparison with UAS-collected structure data.

Figure 11 shows graduate student Robert Huber collecting geologic structure in the traditional fashion, using rope access techniques for rappelling and climbing the slope face at the Deerfield site. This method requires more time to complete than UAS flights, does not cover all parts of a slope face, and might place personnel in hazardous situations. In addition to the Deerfield site, rope access techniques were also used at the Afton Mountain site for collecting structure data.

Figure 11. Graduate student Robert Huber using rope access to safely collect geologic structure data at the Deerfield site in the traditional manner. This method is less efficient than newer UAS techniques and can place personnel in hazardous situations.

Task 6 - Analyze traditionally collected data for design and mitigation purposes

Analyzing geologic structure data for rock slope design and mitigation purposes involves two steps, regardless of the data source. First, kinematic tests are performed using stereonet plots, to determine whether rockslides and rockfalls are physically possible. Second, if the stereonet analyses reveal discontinuity cluster orientations that could lead to failures, it becomes necessary to calculate slope safety factors to assess their severity. Stability analyses using traditionally collected data have been performed for both Site #2 Deerfield and Site #5 Afton Mountain. Only results for Deerfield are reported here.

Site #2, Route 629, Deerfield

The Deerfield site has been the focus of traditional stability studies for over twenty years. It was the location of a significant structurally-controlled rockslide in May 2009 (Figure 12). In 2016-2017, graduate student Rachael Delaney performed geological mapping of the site, under the direction of Dr. Skip Watts of Radford University and Dr. Abdul Shakoor of Kent State University. Those traditionally-collected data and results were analyzed for slope stability, along with Radford University data collected in 2018-2019, as part of this VTRC-funded research.

Stereonet plots of the traditional ground-based orientation data are shown in Figures 13a, 13b, and 14. Figure13a shows the raw data plotted as individual dip vectors using *RockPack III* software. Figure 13b adds Markland’s Test for slope stability. Figure 14 also shows Markland’s Test for stability, plotted using RocScience *DIPS* software. Discontinuity orientations have been contoured in Figure 14 to highlight clusters (population centers), of discontinuities. Figures 13b and 14 both reveal the potential for plane and wedge failures within the rock mass.

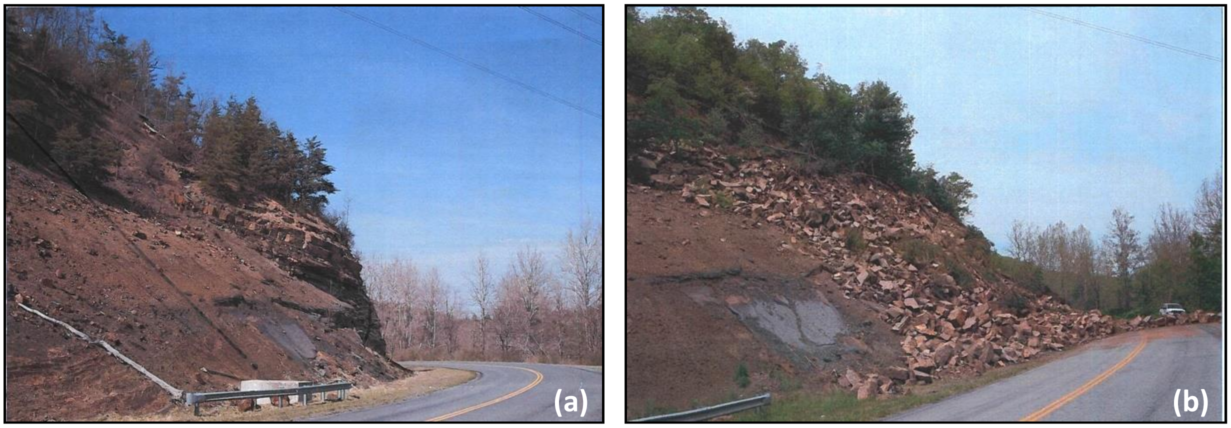

Figure 12. (a) Site #2 Deerfield prior to the May 2009 structurally-controlled rockslide. (b) Same site after the rockslide. Route 629 is seen to be blocked by event. Both pictures are looking to the northeast. Photos provided by Brian Bruckno, VDOT.

Readers who are not familiar with techniques for depicting the orientations of planes in space on stereonets, or with the application of stereonets to stability analyses, are encouraged to read *Using Dip Vectors to Analyze Structural Data*, Whisonant & Watts (1989).

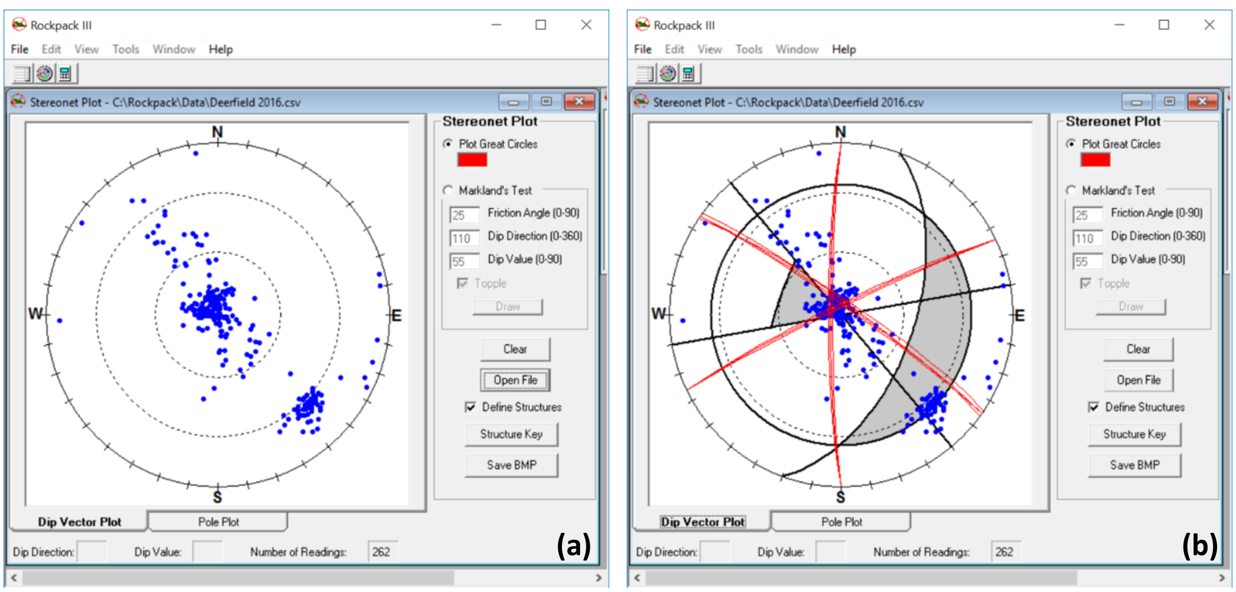

Figure 13. (a) Site #2 Deerfield data, 262 discontinuity orientations, collected by traditional means and plotted as individual dip vectors on a standard stereonet using *RockPack III* software. (b) Same data plotted as individual dip vectors and tested using Markland's Test for potential rock slope failures. These stereonets reveal possibilities for both plane and wedge failures.

Kinematic Analysis

Kinematic analyses take into account the geometry of discontinuities with respect to slope faces. Markland's Test is a type of kinematic analysis. If it reveals that failures are geometrically possible, then safety factors are calculated taking into account driving and resisting forces. Tests reveal that the Deerfield site has the potential for both plane and wedge type failures. Possible plane failures are shown most clearly in Figure 13b by the cluster of blue points in the southeast quadrant on the edge of the crescent-shaped and shaded Markland critical zone. Potential wedge failures are revealed in Figure 13b and in Figure 14, by the intersecting great circles (arcs) shown in red, within or close to the "Critical Intersection Zone for Wedge Failure" labeled in Figure 14.

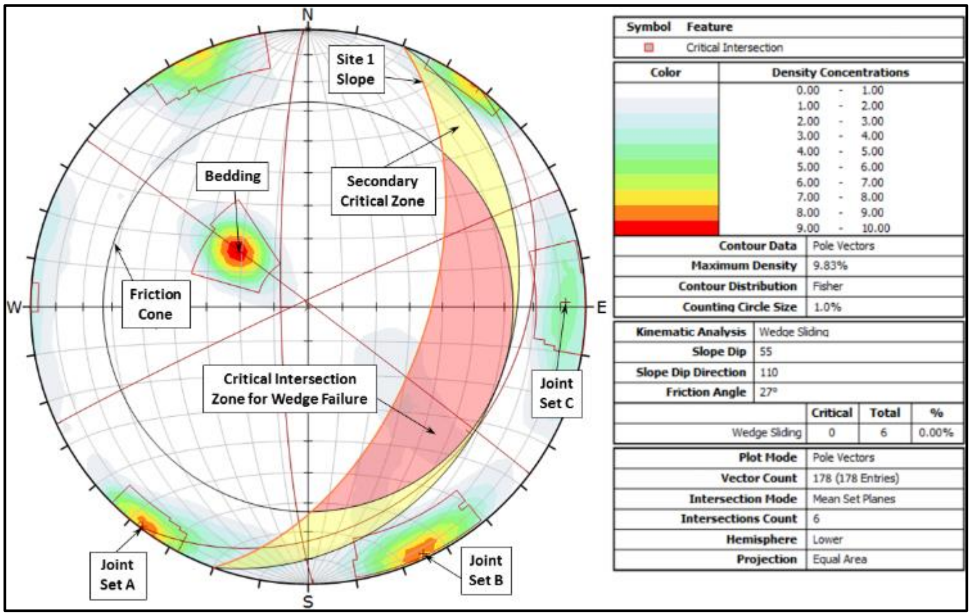

Figure 14. Transit compass data for Deerfield, plotted as poles, rather than dip vectors, and contoured for kinematic stability analysis on a standard stereonet using *DIPS* software (from Delaney, et al., 2020). Bedding plane discontinuities and three joint discontinuity clusters are revealed and labeled as Joint Set A, B, and C. This can be compared with dip vector plots of the same data in Figure 13b.

The stereonets from these traditionally collected data indicate that four clusters of discontinuities are prominent in the rock mass (Delaney, et al., 2020) and were designated as principal discontinuity sets, or PDSs. The four clusters consist of bedding planes, dipping to the southeast at about 26°; and, joint sets A, B, and C, all dipping nearly vertically to the northeast, northwest, and west respectively.

Safety Factor Analysis

After kinematically identifying discontinuities with orientations that could lead to structurally-controlled failures, standard practice calls for calculating factor of safety values for those potential rockslides. For this research, limiting equilibrium methods were used. That is to say: 1) the sum of all driving forces is estimated for a potential slide block, including the vector components of gravity; 2) the sum of all resisting forces is estimated along the potential discontinuity slip surface, including cohesion and friction; and 3) the ratio of the resisting forces divided by the driving forces is calculated. That ratio is termed the factor of safety (FS). If resisting forces are greater than driving forces, the FS value is greater than 1.0 and sliding is theoretically not possible.

Based on the slope geometries determined on site during data collection, and on the average orientations of discontinuities measured from stereonets, the safety factor for planar sliding is 1.03, very close to equilibrium and potential failure. The safety factor for wedge sliding would also be 1.03 in this case, since the geometry here results in sliding on one plane only, while the opposing plane in the wedge acts only as a release surface.

Task 7 - Fly the sites with UAS to collect aerial imagery

The data obtained during this research were collected in several formats by a variety of aircraft and sensors. Data were processed using different methods and software applications, as applicable to the research objectives for each site and the desired deliverables. The nature of the flights also depended on the physical characteristics of the site itself, which always influence flight planning and safety. Details pertaining to flight planning at each site are described below.

Specifically, some missions were also flown manually, that is, operators physically controlled the aircraft at all times, often referred to as "stick-and-rudder" flying. First person view (FPV) is provided using smart phones or tablet computers allowing the operator to see vicariously what the UAV camera sees. Other missions were flown autonomously, that is, controlled by flight planning software, allowing operators to pre-program missions to fly certain patterns and to collect specific types of imagery. The two types of flight require different skill sets and many hours of training time.

The Radford University FAA-registered aircraft that were available for this research included the following models. Sometimes multiple aircraft of the same model were utilized at a site:

1. DJI Phantom Pro
2. DJI Mavic Pro
3. DJI Mavic Pro2
4. DJI Matrice 600
5. 3DR Solo
6. Sensefly Albris
7. Sensefly eBee

Available flight control software included:

1. *DJI Go*
2. *DJI Go4*
3. *eMotion3*
4. *Pix4D Capture*
5. *DJI Ground Station Pro*

Flight plans and flight safety procedures were established by UAS operators and approved by the FAA-certified remote pilot in command (RPIC). Image data were downloaded from UAV SD storage cards to external hard drives and to secure online storage sites for processing.

UAS Test Site #1 - Interstate 77, Multiple Mileposts, Fancy Gap Mountain, Virginia

Flight Environment: A sample flight from this location is shown in Figure 15. This site consists of three separate rock slope work zones close to each other on I-77, near Fancy Gap. The specific locations are MP 5.4 SB, MP 3.8 SB and MP 3.7 NB. The highway consists of two southbound lanes and three northbound lanes, separated by a rugged and rocky, thickly vegetated median. Traffic was heavy during all site visits. The geology consists of metamorphic rocks of the Blue Ridge Province. Joint sets and foliation planes dipping steeply to the southeast dominate in controlling stability. In 1989, Dr. Watts documented a rockslide that blocked southbound lanes and caused detours for over a week at MP 5.4 SB.

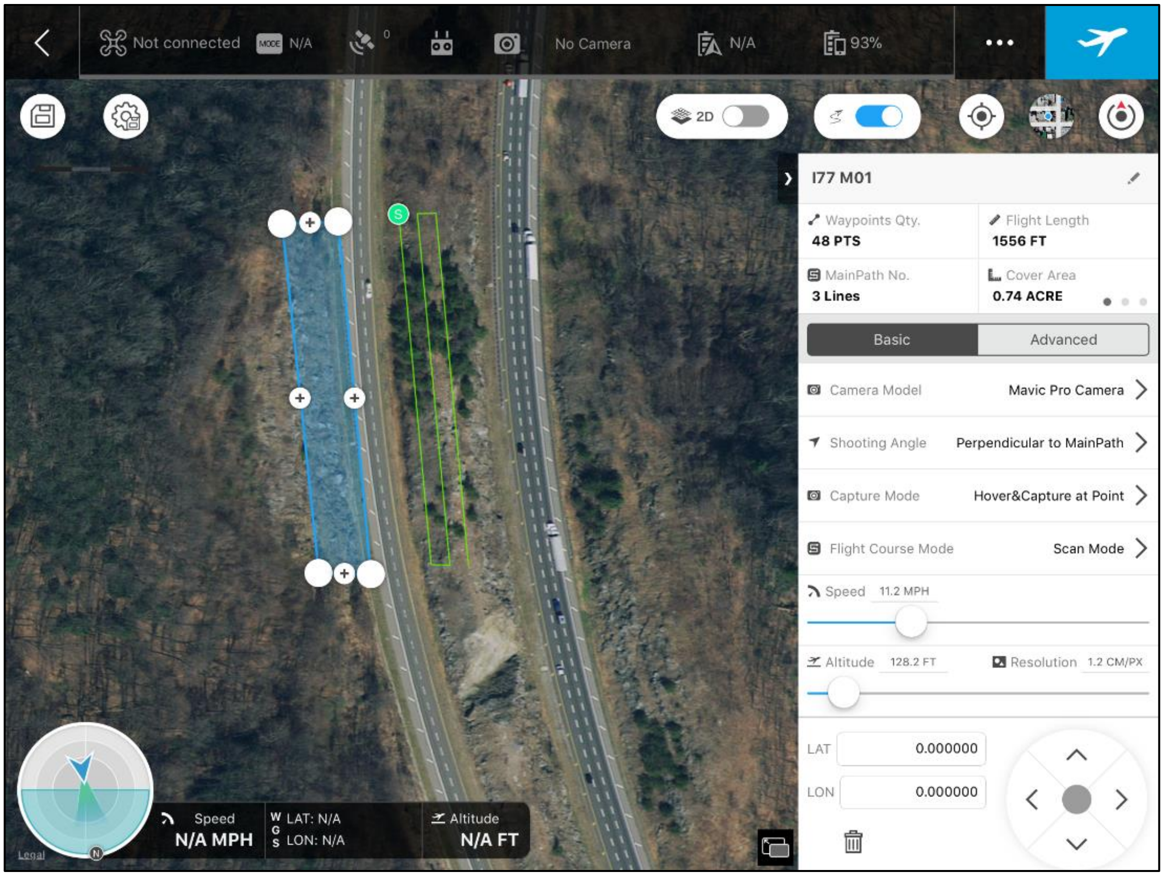

Figure 15. Site #1, I-77 MP 3.8 SB as an example. The blue shaded area represents the imaged portion of the rock slope face. The green lines represent the flight path of the aircraft as it flew sideways, camera facing the slope obliquely for the photogrammetric scan. The flight control software was *Ground Station Pro*.

<u>Flight Planning</u>: The primary goals for the Site #1 work areas were to test the use of small UAS for creating 3D digital models suitable for visualizing the work-in-progress and for estimating areas and quantities, while operating under heavy interstate traffic conditions. The anticipated deliverables were aerial reconnaissance videos and 3D digital models for spatial analysis.

<u>Flight Operations</u>: The following procedures were used to fly the site for collecting and analyzing UAS data:

1. Reviewed and implemented established safety procedures, including:
   - Contractor MOT was in place;
   - Vehicles displayed bright amber strobe lights and workers wore class 3 safety vests;
   - Flight paths did not fly over traffic.
2. Two DJI Mavic Pro drones were selected as UAS platforms, equipped with the manufacturer's stock cameras.
3. One or two video reconnaissance missions were flown at each work zone using manual (stick-and-rudder) controls and first-person view (FPV) observation by the operator on iPad mini devices.
4. Multiple autonomous 3D mapping missions were executed at each work zone, using Ground Station Pro (GSP) as the flight control software, on an iPad mini:

- In Figure 15, the blue shaded area outlines the portion of the rock slope face to be imaged;
- The green lines over the median represent the flight UAV flight path; and,
- The aircraft flew sideways, camera angled toward the rock slope obliquely, providing a photogrammetric scan of the steep slope face.

UAS Test Site #2 - Route 629, Deerfield, Virginia

Flight Environment: As shown in Figure 16, the highway consists of two travel lanes on a curve, with no median but wide shoulders. Traffic was light during the RU visits and no traffic control, other than VDOT signage, was utilized. During previous flights, in collaboration with a contractor, GeoStabilization International, VDOT provided full traffic control and stopped traffic for 10 to 15-minute periods during manual scanning flights. Later site visits included signage, but not flaggers.

Flight Planning: The primary goal at the Deerfield site was to test the use of small UAS to create 3D digital models for testing the use of change detection software for identifying areas of higher rockfall activity by comparisons with 3D models from previous visits.

Flight Operations: The following procedures were used to fly the site for collecting and analyzing UAS data:

1. Reviewed and implemented established safety procedures, including:
   - No contractor or VDOT MOT was needed, other than warning signage;
   - Vehicles displayed amber strobe lights and workers wore class 3 safety vests;
   - Flight paths did not fly over traffic.
2. Two DJI Mavic Pro drones were selected as the UAS platforms, equipped with the manufacturer’s stock cameras.
3. Several video reconnaissance missions were flown to document the site using manual (stick-and-rudder) controls and first-person view (FPV) observation by the operator on iPhones.
4. Multiple manual, “stick and rudder,” 3D mapping missions were executed at the site, using *Pix4D Capture* in Free Flight mode and iPhones as mission control devices:
5. Multiple autonomous 3D mapping missions were executed, using *Pix4D Capture* in Grid mode on an iPhone as the mission control device:
   - In Figure 16, dots outline the imaged portion of the rock slope face.
   - White lines represent the flight path of the aircraft as it flew directly over rock slope.
   - The UAV camera was angled vertically downward for standard aerial photogrammetric mapping.

Figure 16. Site #2, Deerfield. Dots outline the imaged portion of the rock slope face. White lines represent the flight path of the aircraft as it flew directly over rock slope. The UAV camera was looking vertically downward for standard photogrammetric mapping. The flight control software was *Pix4D Capture*.

UAS Test Site #3 - Route 685, River Road, Lynchburg, Virginia

Flight Environment: Figure 17 illustrates a sample mission. The highway consists of two travel lanes on a relatively straight road with no median and with narrow shoulders. Two turnouts are present on the south side near the river bank for mission staging, launching, and landing.

The location presents a difficult environment for flying the sideways flight patterns needed for slope scanning. The shoulder-to-shoulder road width is narrow and the road lies between the steep heavily-vegetated rock slope to the north and tall overhanging trees on the river bank to the south. It was selected for its particular challenges to UAS flights, even during a leaf-off time of year.

Flight Planning: In addition to UAS photogrammetry, laser survey techniques were to be used in a test of penetrating the dense vegetation. For preliminary testing purposes, a UAV LiDAR unit was mounted on a field vehicle and driven along the highway to scan the rock slope. Unfortunately, the LiDAR was later destroyed during a quarry test flight before highway flights were scheduled. The LiDAR unit has not been replaced and remains at the factory at this time.

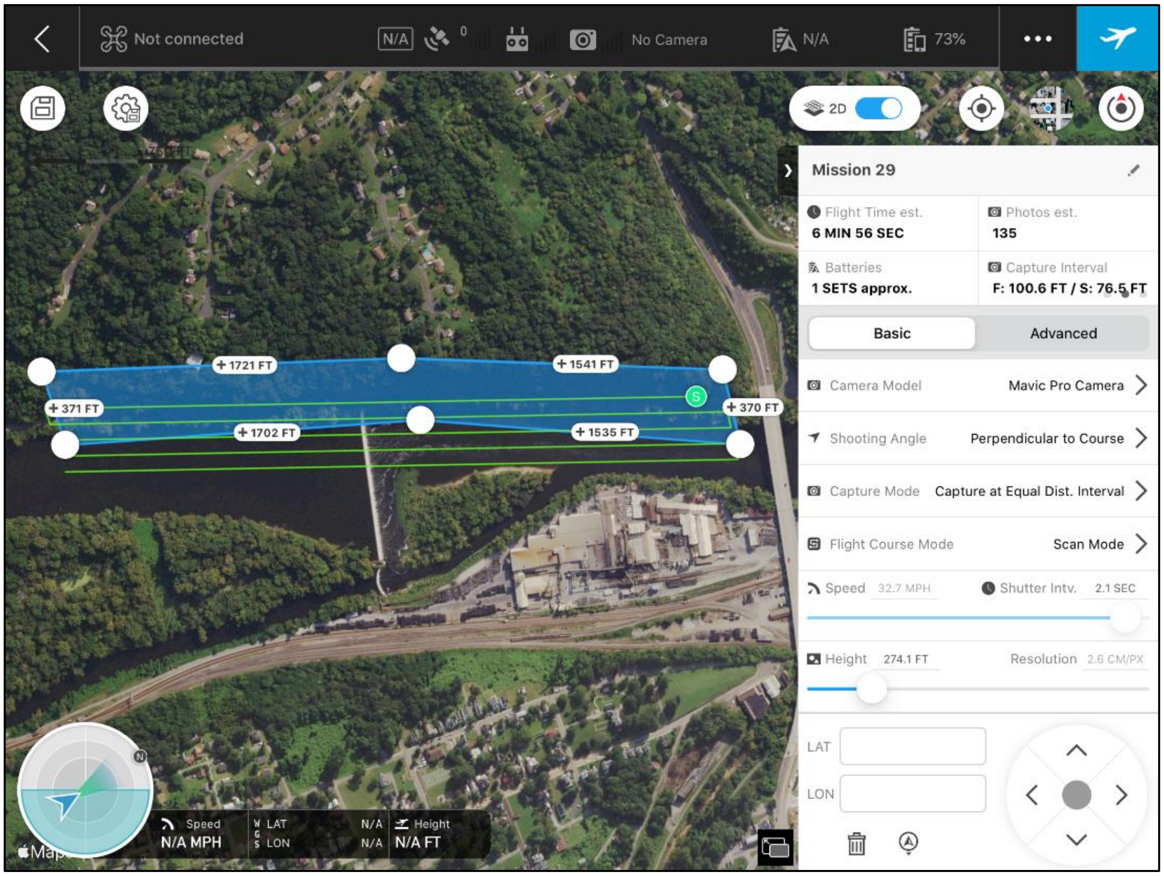

Figure 17. Site #3, Lynchburg. The blue shaded area represents the imaged portion of the rock slope face. The green lines represent the flight path of the aircraft as it flew sideways, camera facing the slope angled obliquely for the photogrammetric scan. The flight control software was *Ground Station Pro*. Most of the flight path was over the James River.

<u>Flight Operations</u>: The following procedures were used for the UAS missions collecting photogrammetric data for 3D modeling and for comparison to the vehicle-mounted mobile Lidar results.

1. Reviewed and implemented established safety procedures, including:
   - VDOT MOT was not needed on Route 658, however, signage and VDOT personnel were positioned on the Route 11 bridge over the James River to protect the FAA-required visual observer (VO);
   - Vehicles on Route 658 and Route 11 displayed bright amber strobe lights and workers wore class 3 safety vests;
   - Flight paths did not fly over traffic.
2. One DJI Mavic Pro drone was selected as the UAS platform, equipped with the manufacturer's stock camera and with high-intensity white strobe lights to enhance visibility for visual observers.
3. White strobe lights were mounted to the aircraft to increase daytime visibility for VOs.
4. Three mobile LiDAR scans of the slope were completed from road level, using the vehicle-mounted Velodyne Puck system from LiDAR-USA.
5. Several <u>manual</u> video reconnaissance missions were executed from above the James River, for both overall site characterization and sideways slope scanning. Missions were flown using <u>manual</u> (stick-and-rudder) flights and first-person view (FPV). The *DJI GO 4* application on an iPad mini was used as flight control software.

6. Three autonomous 3D scanning missions were executed, flying sideways scanning missions from above the James River, using the *Ground Station Pro* (GSP) application in grid mode. An iPad mini was used as the mission control device.
7. The consequences of the loss of UAS-borne LiDAR data at this heavily vegetated site are significant. While Pix4D SfM software does have the ability to strip vegetation and estimate bare earth models, it is not as accurate as LiDAR with the ability to parse point clouds for ground returns only. This is a limitation of photogrammetry at this time. Nevertheless, photogrammetry is an order of magnitude less expensive making it most practical for the majority of sites where rock slopes are bare and rock structure is well exposed.

UAS Test Site #4 - Route 340, Harpers Ferry, Virginia

Flight Environment: Site #4, shown in Figure 18, consists of a low rock and soil cut on Virginia Route 340, adjacent to the 340 bridge over the Potomac River near Harpers Ferry, West Virginia. The slope is at the east end of a short, approximately 0.5 mile, stretch of Virginia highway, bounded on the west by the West Virginia state line and on the east by the Maryland state line. The highway consists of three lanes with broad shoulders beneath a dense canopy of trees. There is no median; however, the center lane is used as a turning lane, or as a no-travel lane at some locations.

Flight Planning: The primary goal was to test the use of small UAS for creating 3D digital models suitable for measurements and creating contour maps directly from aerial imagery. The anticipated deliverables were aerial reconnaissance videos, 3D digital models, and CADD-ready maps. Of particular need at this site was a topographic map of the work area for contractor HDR. Flights were planned accordingly.

Flight Operations: The following procedures were used to fly the site and collect and analyze UAS data:

1. Reviewed and implemented established safety procedures, including:
   - Contractor warning signage was provided by HDR;
   - Vehicles displayed amber strobe lights and workers wore class 3 safety vests;
   - Flight paths did not fly over traffic.
2. Two DJI Mavic Pro drones and one Mavic Air drone were selected as UAS platforms, equipped with the manufacturer's stock cameras.
3. Several video reconnaissance missions were flown at different altitudes using manual (stick-and-rudder) flights and first-person view (FPV) for the pilot on iPad mini devices.
4. Several manual road-level 3D mapping missions were executed using *Pix4D Capture*, in Free Flight mode, with an iPhone as the mission control application.
5. Two autonomous 3D mapping missions were executed at different altitudes above tree tops, using *Ground Station Pro* (GSP) and an iPad mini as the mission control software.

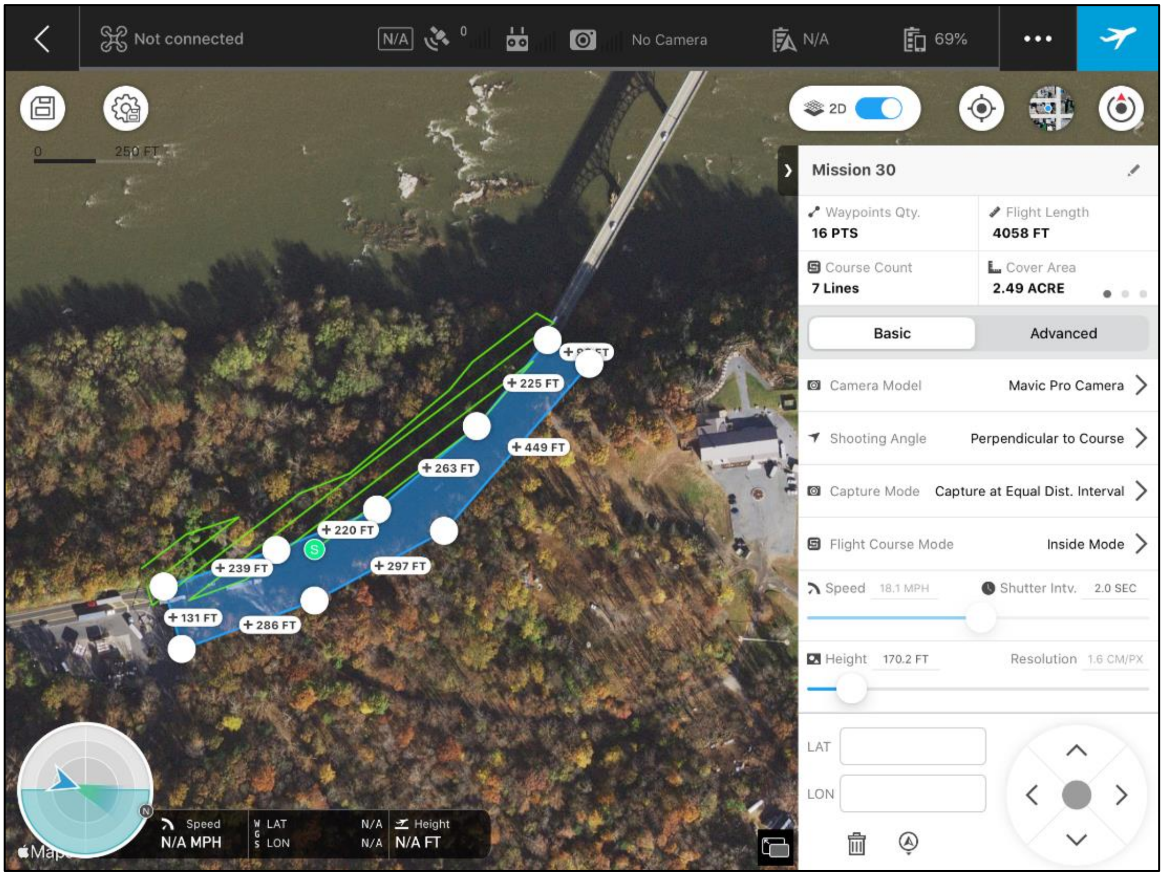

Figure 18. Site #4, Harpers Ferry. The blue shaded area represents the imaged portion of the rock and soil slope face. The green lines represent the flight path of the aircraft as it flew sideways, camera facing the slope angled obliquely for the photogrammetric scan. The flight control software was *Ground Station Pro*. The flight path was over the wooded area between the highway and the Potomac River.

UAS Test Site #5 - Interstate 64 Milepost 101 WB, Afton Mountain, Virginia

Flight Environment: The highway consists of four Interstate lanes, two westbound and two eastbound, separated by gentle grassy median (Figure 19). The alignment is relatively straight as the Interstate rises in the westward direction toward the crest of Afton Mountain. Traffic was heavy during the RU visits, but line-of-site visibility was good. Royal Orchard Drive crosses I-81 at this location on a state-maintained bridge. The bridge deck and adjacent areas provided adequate UAS launch zones and work areas that were well away from the traffic lanes.

Flight Planning: The primary goal at the Afton Mountain site was to test the use of small UAS to create time-stamped 3D digital baseline models for analysis and also for possible change detection analysis in the future. The Afton Mountain site is also considered important in that Dr. Yonathan Admassu of James Madison University has previously used this site for rockfall rating analyses under contract to VTRC. The results of these UAS missions could be of comparative value to him over time.

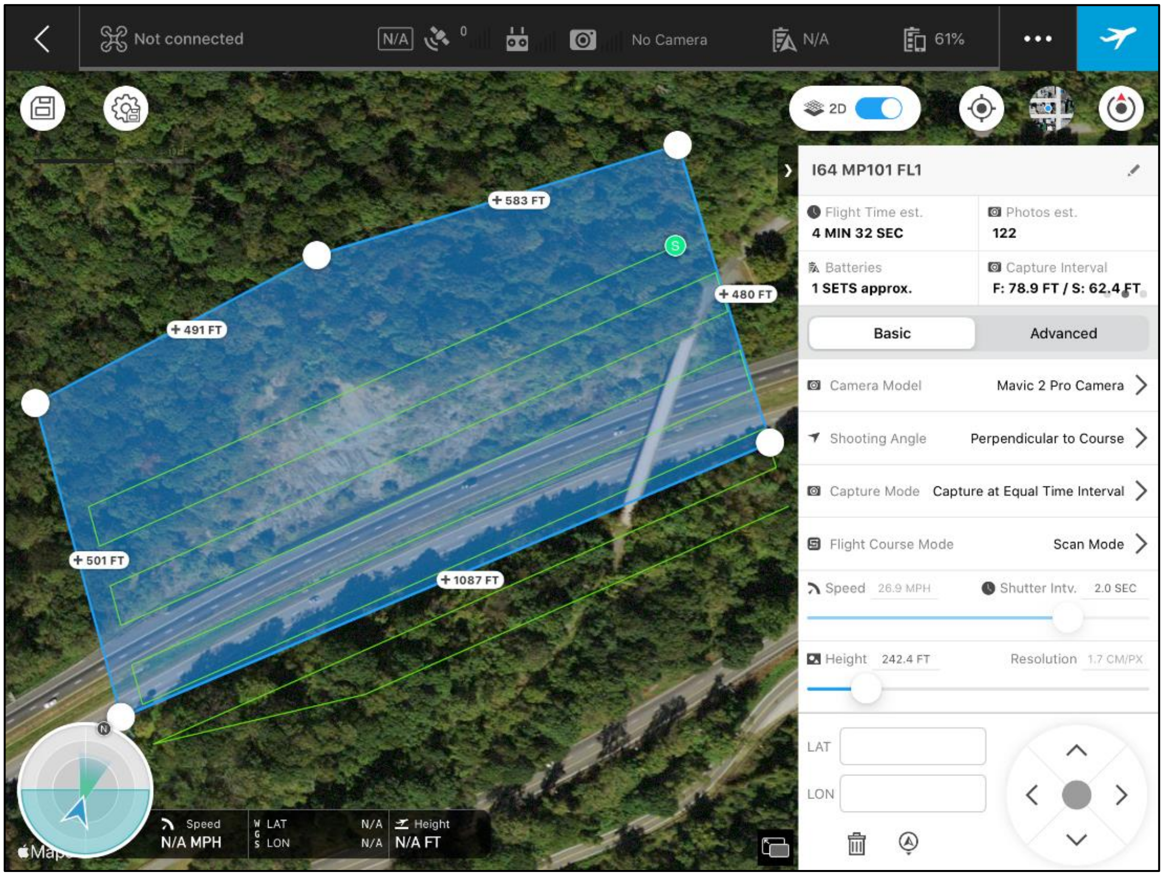

Figure 19. Site #5, Afton Mountain. The blue shaded area represents the imaged portion of the highway and the rock slope face. The green lines represent the flight path of the aircraft as it flew sideways, camera facing the slope angled obliquely for the photogrammetric scan. The flight control software was *Ground Station Pro*. The flight lines were parallel to the highway. Flights were timed and paused as needed with the assistance of VOs to enable flying over the highway during breaks in traffic flow.

Flight Operations: The following procedures were used to fly the site and collect and analyze UAS data:

1. Reviewed and implemented established safety procedures, including:
   - VDOT warning signs were provided on Interstate 64, up-traffic from the active flight zones, no other VDOT personnel or vehicles were deemed necessary;
   - Missions launched and returned to locations away from the Interstate, to the north of the Royal Orchard Drive bridge over the Interstate;
   - Ground control points were placed and surveyed within the I-64 shoulders;
   - Vehicles displayed amber strobe lights and workers wore class 3 safety vests;
   - Flight paths did not fly over the highway while traffic was present.
2. Two DJI Mavic Pro drones were selected as the UAS platforms, equipped with the manufacturer's stock cameras.
3. Several manual video reconnaissance missions were executed across the site using manual (stick-and-rudder) methods and first-person view (FPV) was provided for the UAV operators on iPad mini devices.
4. Multiple autonomous 3D mapping missions at the site, using *Pix4D Capture* and *Ground Station Pro*, in Polygon mode, with an iPad mini as the mission control device.

UAS Test Site #6 - Interstate 81 Milepost 126.7 SB, Ironto, Virginia

Flight Environment: Interstate-81 at Site #6, shown in Figure 20, consists of five traffic lanes, three southbound and two northbound, separated by a rugged and rocky median, in a narrow valley on a relatively straight alignment. The northbound lanes are at a considerably lower elevation than the southbound lanes.

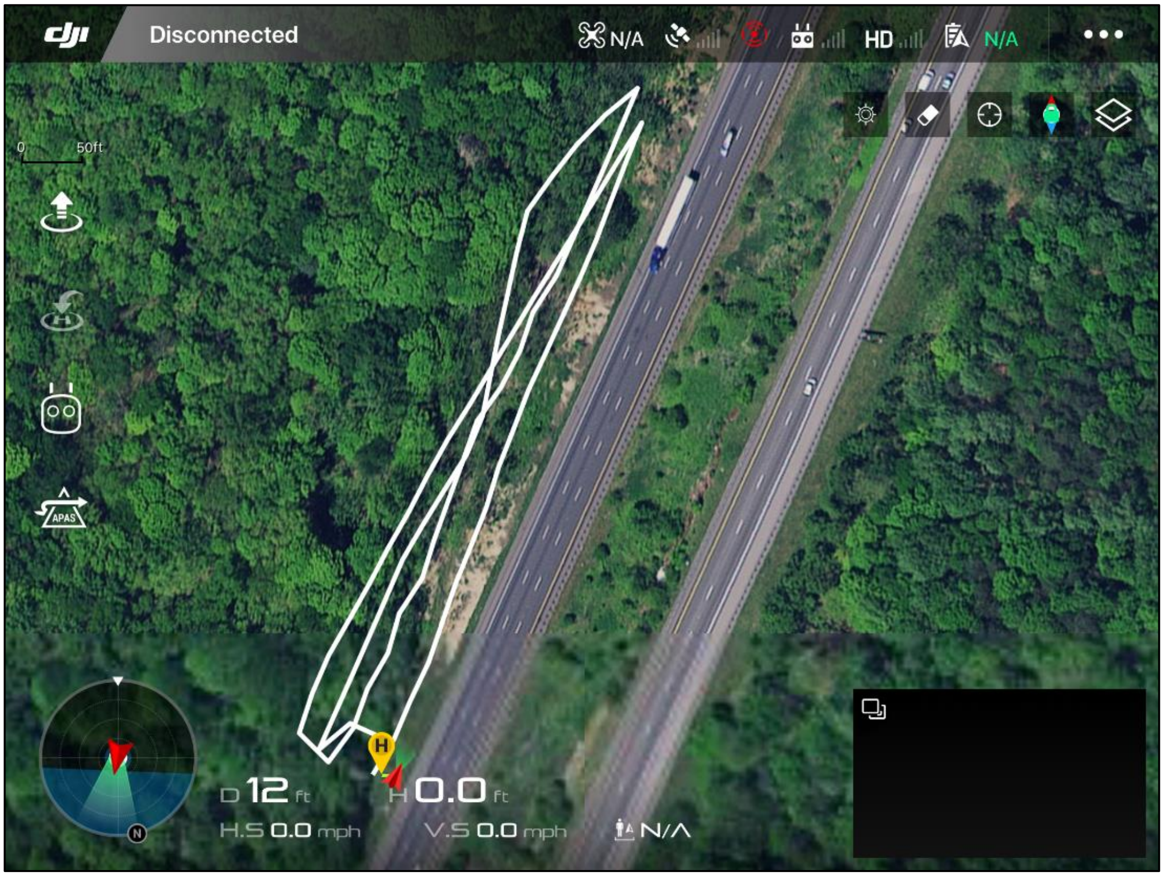

Figure 20. Site #6, Ironto. The irregular white flight path shown is characteristic of a manual "stick-and-rudder" mission, in contrast to the programmed autonomous flights depicted for previous flights. Manual flight by a skilled operator was deemed necessary due to the irregular terrain, high vegetation, and the narrow valley. Time was insufficient for programming safe flights in this setting. The figure depicts a video reconnaissance flight using *Pix4D Go* for flight control on an iPad mini.

This environment made it challenging to fly the necessary sideways scan of the slope without the aircraft passing over travel lanes. No autonomous flights were attempted at this location; all flights were manual "stick-and-rudder" due partly to time constraints. Traffic was heavy. The contractors, GeoStabilization International and HDR, had established a well-protected work area using a lane shift, shoulder closure with concrete barriers, and signage.

Flight Planning: The primary goal at the Ironto site was to test the use of a small UAS with a higher camera resolution, to create 3D digital models for quantifying site characteristics and also for change detection analysis if needed in the future. This was a site-of-opportunity that arose when the slide became active. The resulting 3D models are to be preserved and may be of future value as a baseline for comparison over time.

Flight Operations: The following procedures were used to fly the site and collect and analyze UAS data:

1. Reviewed and implemented established safety procedures, including:
   - Contractor MOT was in place;
   - Missions launched and returned to locations adjacent to the Interstate, behind a concrete barrier;
   - Vehicles displayed amber strobe lights and workers wore class 3 safety vests;
   - Flight paths did not fly over the highway while traffic was present.
2. One new DJI Mavic Pro2 drone was selected as the UAS platform, equipped with a high-resolution Hasselblad camera with outstanding resolution and clarity.
3. Several video reconnaissance missions were executed across the site using manual techniques and first-person view (FPV) for the pilot on iPad mini devices.
4. Two manual stick-and-rudder 3D mapping missions at the site, using *Pix4D Capture*, in Free Flight mode, with an iPad mini as the mission control device.

UAS Test Site #7 - Salem Stone, ACCO and Holston Quarries, Blacksburg and Dublin, Virginia

Flight Environment: Site #7a and 7b consist of highwalls located in the Salem Stone, ACCO Quarry, near Blacksburg, and the Holston Quarry, near Dublin. Figure 21 shows a programmed autonomous flight at 7b. Quarries were suggested for inclusion in this study for several reasons: (1) they are away from the traveling public, aircraft hardware and software can be tested without concern for the safety of motorists; and, (2) quarries are excellent locations for testing change detection software, since the active highwalls change frequently.

Flight Planning: The primary goals at the two Salem Stone quarry sites were to test aircraft, flight software, and different sensors under a variety of conditions for both large and small UAS, before taking them to areas near traffic. In particular, the use of DJI Mavic Pros for creating detailed point cloud models for dimensional analyses over time was desired. Flight tests using the heavy-lift, DJI Matrice 600 UAV, to carry a drone-borne LiDAR scanning unit, were planned for the ACCO Salem Stone quarry as well as at the Dublin quarry.

Flight Operations: The following procedures were used to fly the site and collect and analyze UAS data:

1. Reviewed and implemented established safety procedures, including:
   - UAS flight crews attend mine safety training;
   - Mine personnel briefed on flight operations and expectations;
   - Missions take off and land at locations approved by the mine manager;
   - Missions programmed by UAS operator and approved by the RPIC.
2. DJI Mavic Pro drones were selected as UAS platforms, equipped with the manufacturer’s stock camera.
3. The Radford University heavy-lift Matrice 600 UAV was prepared for use with the LiDAR laser scanner.
4. Several Mavic Pro 2 video reconnaissance missions were executed over mine highwalls using manual (stick-and-rudder) flights and first-person views (FPV) for the operator on iPad mini devices.
5. Several autonomous 3D mapping missions at the site were executed, using *Ground Station Pro*, in polygon mode, with an iPad mini as the mission control device.

6. Test flights with the heavy lift DJI M600 carrying the LiDAR-USA laser scanner were executed. The final test flight terminated as a result of a crash into a quarry highwall due to a mission programming error.

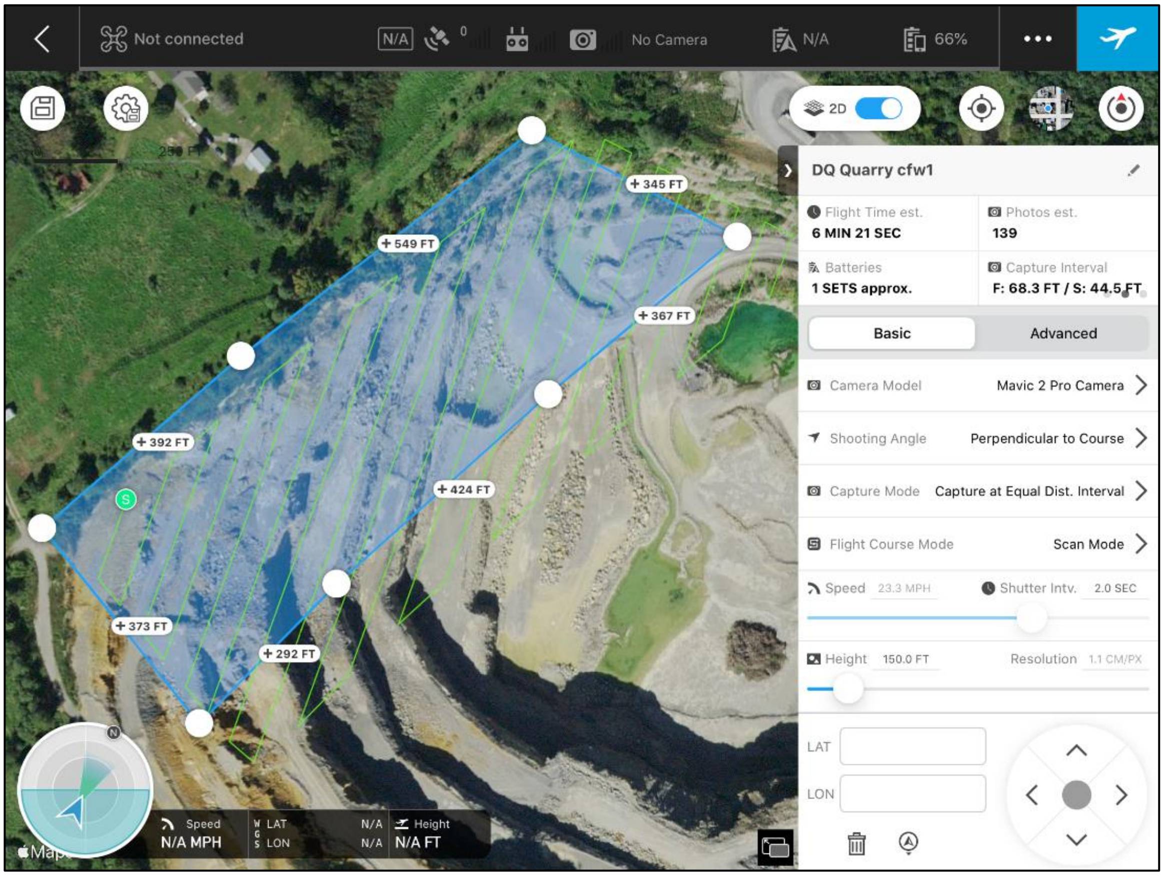

Figure 21. Site #7, Salem Stone Holston Quarry, Dublin. The blue shaded area represents the imaged highwalls in the quarry. The green lines represent the flight path of the aircraft as it flew sideways, camera facing the slope angled obliquely for the photogrammetric scan. The flight control software used was *Ground Station Pro*.

Task 8 - Process UAS imagery for design and mitigation purposes

Many data processing options are available depending on the tasks to be accomplished and the deliverables needed to assist with rock slope design and mitigation. This section highlights processing options related to the unique needs of each site.

The data collected during this research consist primarily of high-resolution still photographs and high-definition (HD) video imagery. Limited LiDAR (light distance and ranging) data were also obtained prior to the crash of the LiDAR-bearing Matrice 600 UAV. Point clouds generated by LiDAR scanning are similar to, and complement, point clouds generated by structure-from-motion photogrammetry.

The following are examples of deliverables that can be derived from UAS imagery for use in rock slope design and mitigation:

1. Individual high-resolution images;
2. High-definition video;

3. Digital computer models for quantifying slope geometries and extracting geologic structure data for kinematic stereonet stability analyses;
4. Animated videos of computer-generated 3D computer models;
5. Physical 3D-printed models of rock slopes;
6. Orthophoto mosaic maps as GIS layers for design purposes;
7. Contour maps as GIS layers, suitable for creating cross sections; and
8. High-altitude, virtual-reality simulations, for interactive site inspections.

Site #1 Processing - Interstate 77, Multiple Mileposts, Fancy Gap Mountain, Virginia

Site Factors: The geology consists of metamorphic rocks of the Blue Ridge Province of southwestern Virginia (Figure 22). Joints and foliation planes are dipping steeply to the southeast, controlling stability.

For the southbound lanes, weathering along joint sets weakens support beneath large rock slabs allowing them to periodically detach and slide down to the shoulder and to roadway below. For the northbound lanes, these dominant joint sets dip into the rock mass and away from the highway. This eliminates large-scale sliding along those surfaces, but results in smaller, less dominant joints forming a rugged back slope, subject to failures of rock blocks falling and rolling down to the roadway.

Rock scaling and mitigation by installing rockfall mesh were being employed at the time of this investigation. The primary goal here was to document slope geometry and test software for measuring quantities of applied mesh for cost estimates.

Processing Options: The following options were used to process imagery for this site.

1. Aerial reconnaissance videos were captured and archived for all three locations.
2. High resolution aerial photographs were processed using *Pix4D Mapper* to create colorized point clouds and triangle mesh models.
3. Computer generated videos were made of the rock slope to animate the 3D model from moving perspectives highlighting key features.
4. *Pix4D Mapper* was used for measuring rockfall mesh quantities applied to the slope and for creating slope cross sections, as shown in Figure 22.
5. Contour lines were exported as GIS shape files and plotted in ArcMAP, as shown in Figure 23.

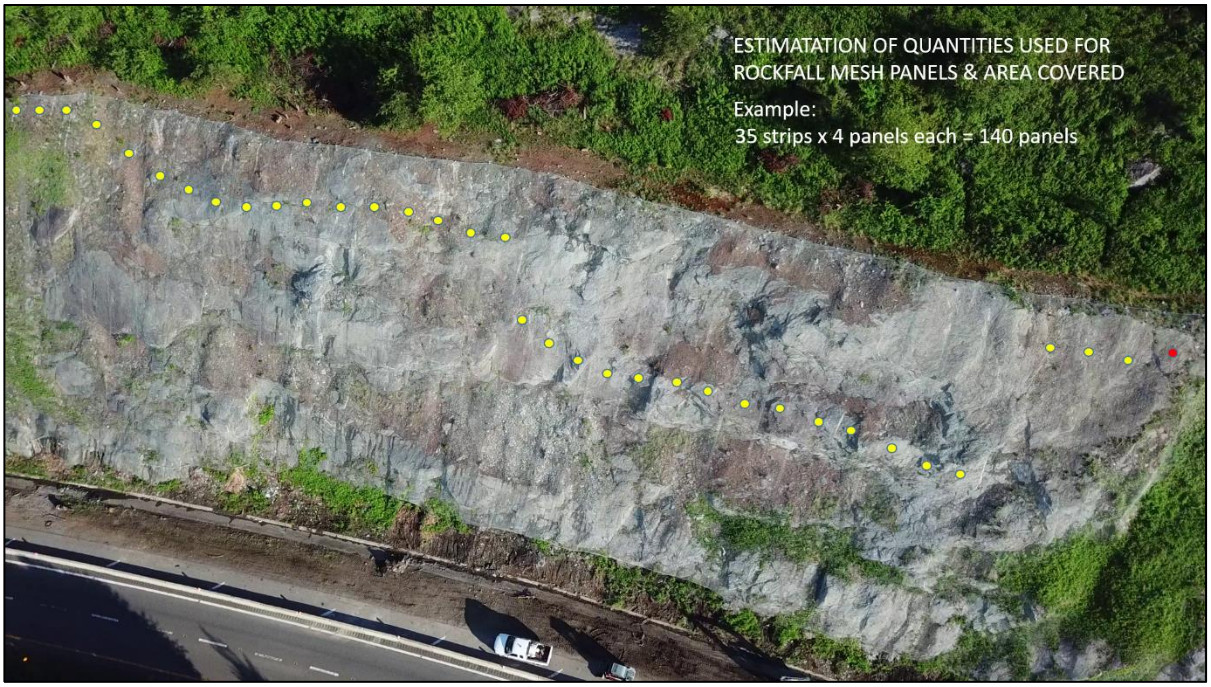

Figure 22. Site #1, I-77 SB MP 5.4, mesh quantity measurements on oblique high resolution still image. It appears that 140 panels were used for just this portion of the site. Yellow dots identify individual strips consisting of 4 vertical panels each.

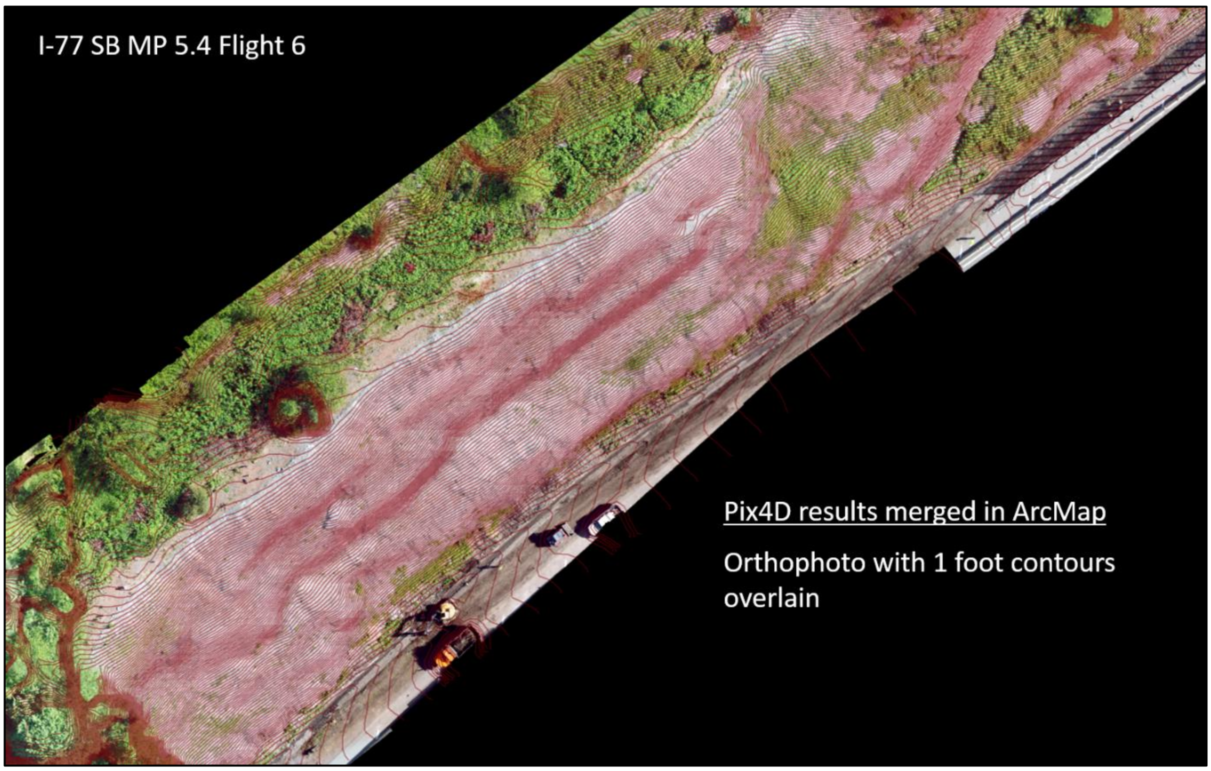

Figure 23. Site #1, I-77 SB MP 5.4, UAS-generated topographic map overlain onto UAS-generated georeferenced orthophoto mosaic from which profile sections can be constructed.

Site #2 Processing - Route 629, Deerfield, Virginia

Site Factors: Site #2 has a history of both major and minor rock slope failures. The most serious occurred in May 2009 when a large rock mass slid along bedding planes and blocked both of the travel lanes. Fortunately, no vehicles were nearby when the slide occurred.

Owing to its history and location, the Deerfield site is perhaps the most investigated rockfall site in Virginia. For more than a decade, different methods have been used to create 3D models at this site including terrestrial photogrammetry by William Niemann of Marshall University, VDOT terrestrial LiDAR, Radford University terrestrial LiDAR, GeoStabilization International UAS photogrammetry, and collaborative Radford University - Kent State University UAS photogrammetry. Repeated imaging over time provides opportunities to evaluate slope deformation using change detection software.

Processing Options: The following options were used to process imagery for this site.

1. Aerial reconnaissance videos were captured and archived for the entire slope.
2. High resolution aerial photographs were processed using *Pix4D Mapper* to create colorized point cloud and triangle mesh models, also known as TINs, along the entire slope, shown as Figure 24.
3. Computer generated videos were made of the rock slope to animate the 3D model from moving perspectives, highlighting key features.

Figure 24. Site #2, Deerfield. UAS point cloud, scaled and georeferenced for obtaining measurements including the extraction of geologic structure data for stability analyses. This model represents conditions in 2016, prior to rock block failures from the rock projection feature in the top center of the image. This is a portion of one of the two point clouds used to test change detection techniques to fulfill of Task #11.

4. Geologic structure data in the form of discontinuity orientations were extracted from UAS point clouds using *CloudCompare* and *Split-FX* for comparison with traditionally collected data (Figure 25). Those results are presented in Task 10.

5. Change detection software was tested for use in identifying areas of higher rockfall activity by merging and comparing point clouds acquired over time. Those results are presented in Task 11.

Figure 25. Site #2, Deerfield. Example of extraction of structure data from UAS-based point cloud for plotting on stereonets (Delaney, et al., 2020).

Site #3 Processing - Route 685, River Road, Lynchburg, Virginia

Site Factors: Although Site #3 has some history of rock slope failures, no Radford University team members had previously worked on rock slope stability issues at this location. It was selected for its unique challenges to UAS flight operations, as described in Task 7 - Flight Operations above.

This site was also to be the location for the first highway flights of the research team's UAS-borne LiDAR system, mounted to a DJI Matrice-600. However, the LiDAR unit was destroyed in a crash during a training flight. Fortunately, the LiDAR data were obtained prior to the crash, by mounting it on a vehicle driving alongside the test slope to simulate a low-altitude UAS LiDAR scan.

Processing Options: The following options were used to process imagery for this site.

1. Aerial reconnaissance videos were captured and archived for the entire slope.
2. High resolution aerial photographs were selected and processed using *Pix4D Mapper* to create colorized point clouds and triangle mesh models along the entire slope (Figure 26).
3. Computer generated videos were made of the rock slope to animate the 3D model from moving perspectives highlighting key features.
4. The truck-mounted mobile LiDAR test data were processed using LiDAR USA's Scanlook Revolution software. A .las formatted point cloud file was generated (Figure 27), similar to .las formatted point clouds generated by UAS photogrammetry, for comparison.

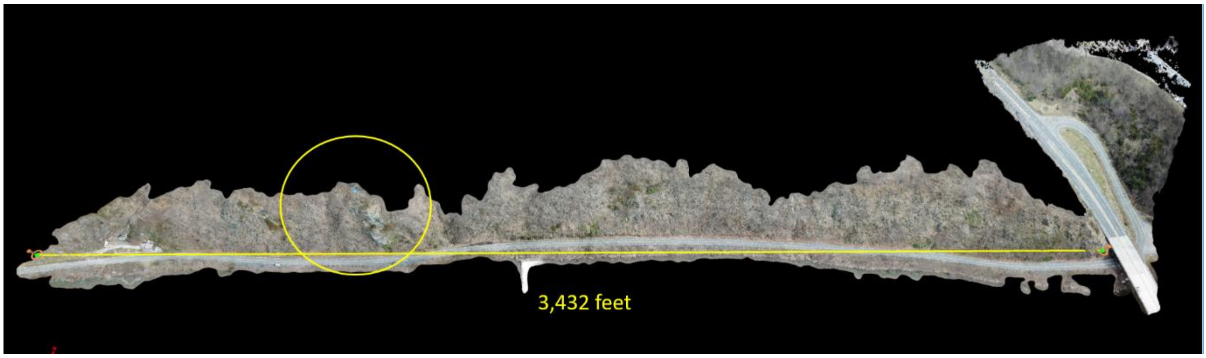

Figure 26. Site #3, Lynchburg. The entire UAS photogrammetric point cloud for the Lynchburg site. The entire point cloud is well-formed and suitable for measurements. The abundant vegetation does make it difficult to quantify data in some areas. It was hoped that UAS-borne LiDAR would provide bare-earth point clouds in those locations.

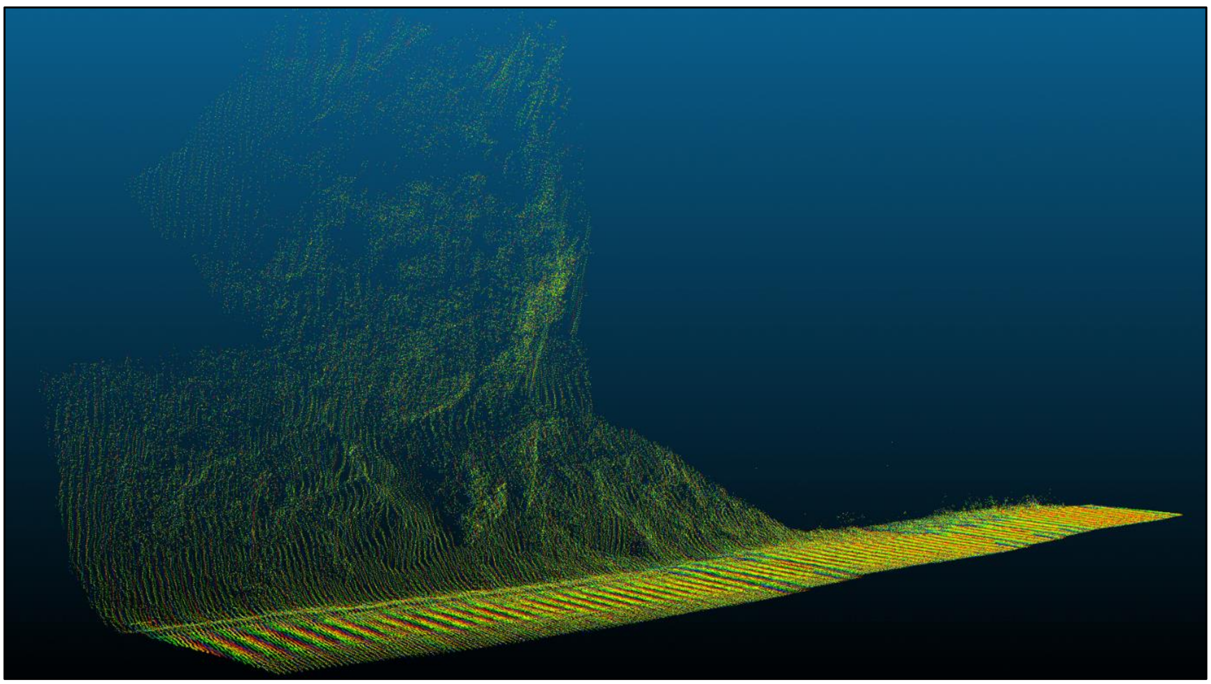

Figure 27. Site #3, Lynchburg. Results of a truck-mounted test of the Radford University LiDAR system for the circled portion of Figure 26. The intent was to test the mobile system first on a road vehicle, then test it on a heavy-lift UAV in a quarry, and finally to return to this location for data-gathering aerial flights. Unfortunately, the LiDAR unit was destroyed in a quarry test flight crash.

Site #4 Processing - Route 340, Harpers Ferry, Virginia

Site Factors: This location was suggested for inclusion in the study as a test site-of-opportunity, in that HDR had a contract with VDOT to prepare a mitigation feasibility plan for the slope. HDR included UAS results from this site in its constructability report to VDOT in the form of a topographic map. The source and funding are referenced as: *Implementation of Unmanned Aerial System-Based (UAS) Digital Photogrammetry for Design, Risk Analysis and Hazard Mitigation of Rock Slopes*, VTRC 114418 ($83,214).

Processing Options: The following options were used to process imagery for this site.

1. Aerial reconnaissance videos were captured and archived for the entire slope.
2. High resolution aerial photographs were selected and processed using *Pix4D Mapper* to create colorized point clouds and triangle mesh models along the entire slope (Figure 28).
3. Computer generated videos were made of the rock slope to animate the 3D model from moving perspectives highlighting key features.
4. A georeferenced topographic map of the site was created from UAS data for HDR to use in mitigation planning and inclusion in reports to VDOT.
5. Profile sections were created from the 3D models using Pix4D Cloud (Figure 29).

Figure 28. Site #4, Route 340, Harpers Ferry, Virginia. This is not a photograph, rather a portion of the georeferenced densified point cloud from which topographic maps and sections (below) were generated by *Pix4D Mapper*. Results were then transferred to *ArcMap* for distribution to HDR for constructability review purposes. This image is a screen capture from a video animation of the dense point cloud.

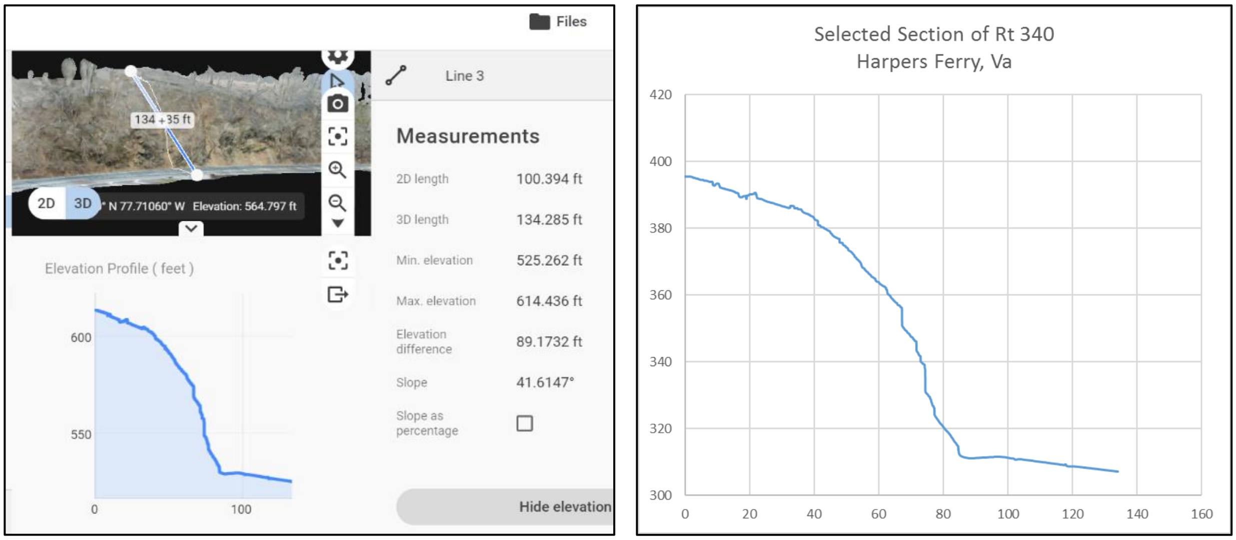

Figure 29. Site #4, Route 340, Harpers Ferry, Virginia. Examples of measurements and station sections that can be created from UAS data using *Pix4D Mapper*, *Pix4D Cloud*, and *ArcMAP*. Results shown are from *Pix4D Cloud*.

Site #5 Processing - Interstate 64 Milepost 101 WB, Afton Mountain, Virginia

<u>Site Factors</u>: Site #5 has a history of both major and minor rock slope failures. It is said that slides caused problems along this portion of I-64, even during construction in the early 1970's, producing excess material that was used to construct the scenic overlook parking area. One of the most serious events occurred at milepost 101 westbound in 1989, when a large rock mass slid along metamorphosed bedding planes. The slide covered the westbound travel lanes, seriously damaged a tractor-trailer and destroyed a car. Fortunately, there were no injuries. Dr. Watts and Radford University colleagues studied several sites here, under contract to VDOT in the 1980's and 1990's, including the milepost 101 location.

<u>Processing Options</u>: The following options were used to process imagery for this site.

1. Aerial reconnaissance videos were captured and archived for the entire slope.
2. High resolution aerial photographs were selected and processed using *Pix4D Mapper* to create colorized point clouds and triangle mesh models along the entire slope (Figure 30).
3. Computer generated videos were made of the rock slope to animate the 3D model from moving perspectives highlighting key features.
4. Point clouds were prepared in .las format for use by Dr. Admassu at James Madison University in his VTRC-funded rock hazard mapping research (Figure 31).

Figure 30. Site #5, Afton Mountain, I-64 Milepost 101. Farthest lanes are westbound. Densified point cloud with overlain triangle mesh, generated from UAS imagery using *Pix4D Mapper*.

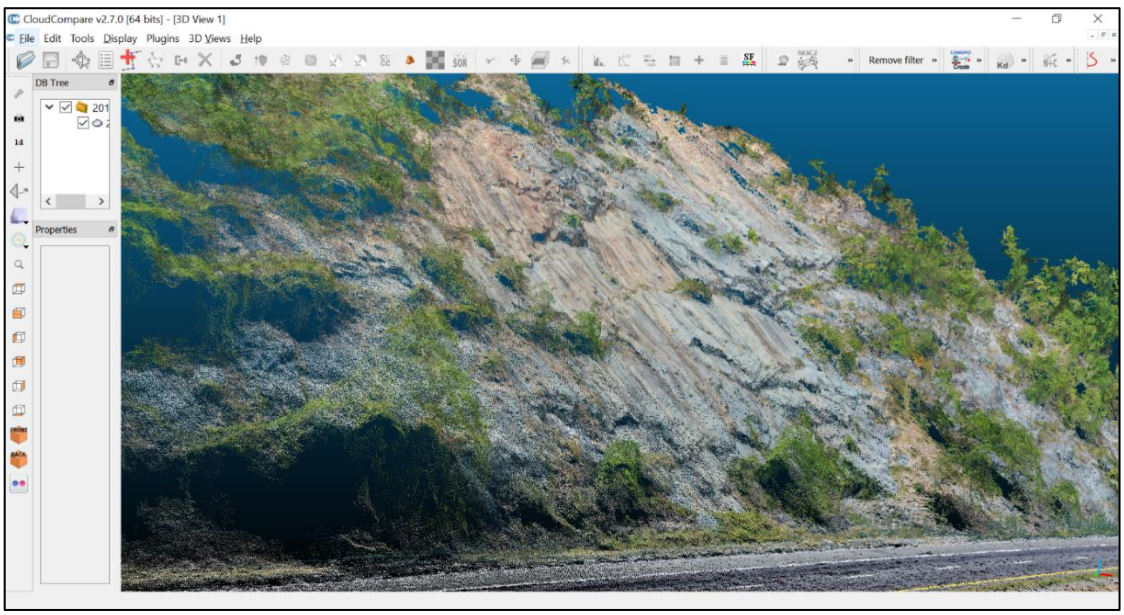

Figure 31. Site #5, Afton Mountain, I-64 Milepost 101. Dense point cloud presented as a simulated LiDAR image in the .las format. Generated from UAS imagery and exported using *Pix4D Mapper*. Displayed in *CloudCompare*.

Site # 6 Processing - Interstate 81 Milepost 126.7 SB, Ironto, Virginia

Site Factors: This section of highway, from MP 128 south to MP 125, has long a history of both major and minor slope failures controlled by complex geologic structures. For example, a very large structurally-controlled slide occurred just south of Exit 128 during construction of the interstate in 1969-1970. That slide delayed the original opening of I-81, from Ironto to Christiansburg, for many months. A similar, but smaller, structurally-controlled slide occurred in 2013 during the construction of truck climbing lanes at milepost 125 southbound. The 2019 slope movements occurred at milepost 126.7. HDR and GeoStabilization International were designated as engineers and contractors to evaluate, design, and mitigate the site.

Processing Options: The following options were used to process imagery for this site.

1. Aerial reconnaissance videos were captured and archived for the entire slope.
2. High resolution aerial photographs were selected and processed using *Pix4D Mapper* to create colorized point clouds and triangle mesh models along the entire slope.
3. Computer generated videos were made of the rock slope to animate the 3D model from moving perspectives highlighting key features.
4. Point clouds were prepared and used to create sections and quantify measurements (Figure 32).
5. UAS flights were conducted two weeks apart at this location to document mitigation progress (Figure 33). Digital 3D models were generated for comparison.

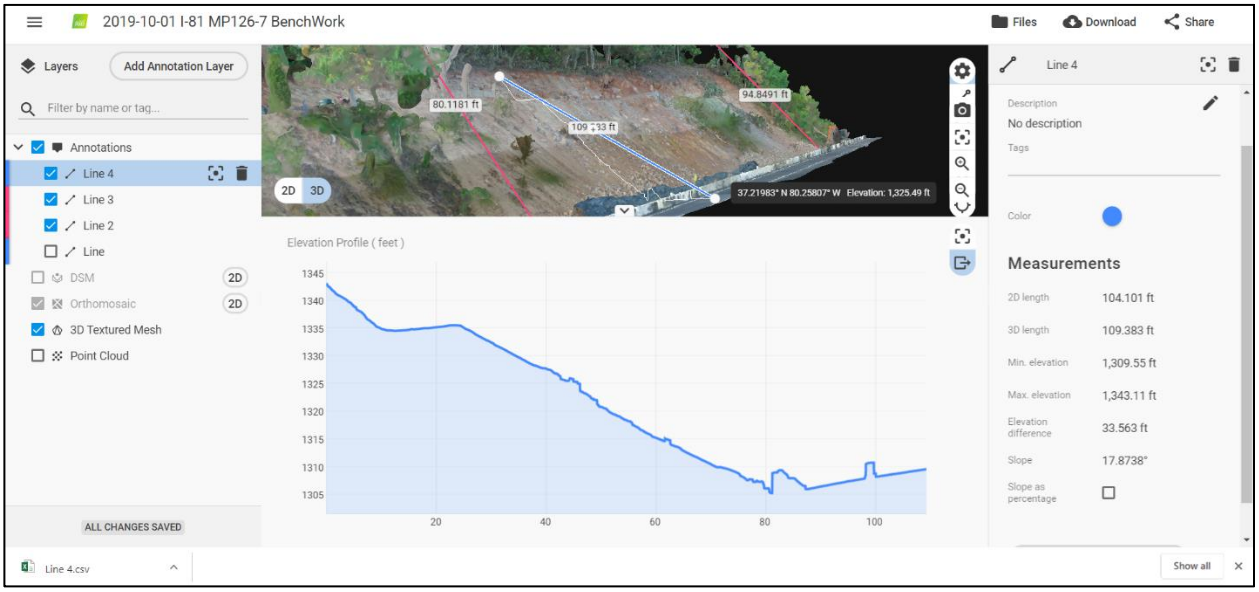

Figure 32. Site #6, Ironto, I-81 Milepost 126.7 Southbound; UAS demo project for GeoStabilization International. Measurements and profile section made on the dense point cloud generated in *Pix4D Cloud*. Note how the UAS 3D model picked up the Jersey barrier on the right side of the profile, the bundled rockfall mesh in the ditch, and some rock slabs resting on the slope face.

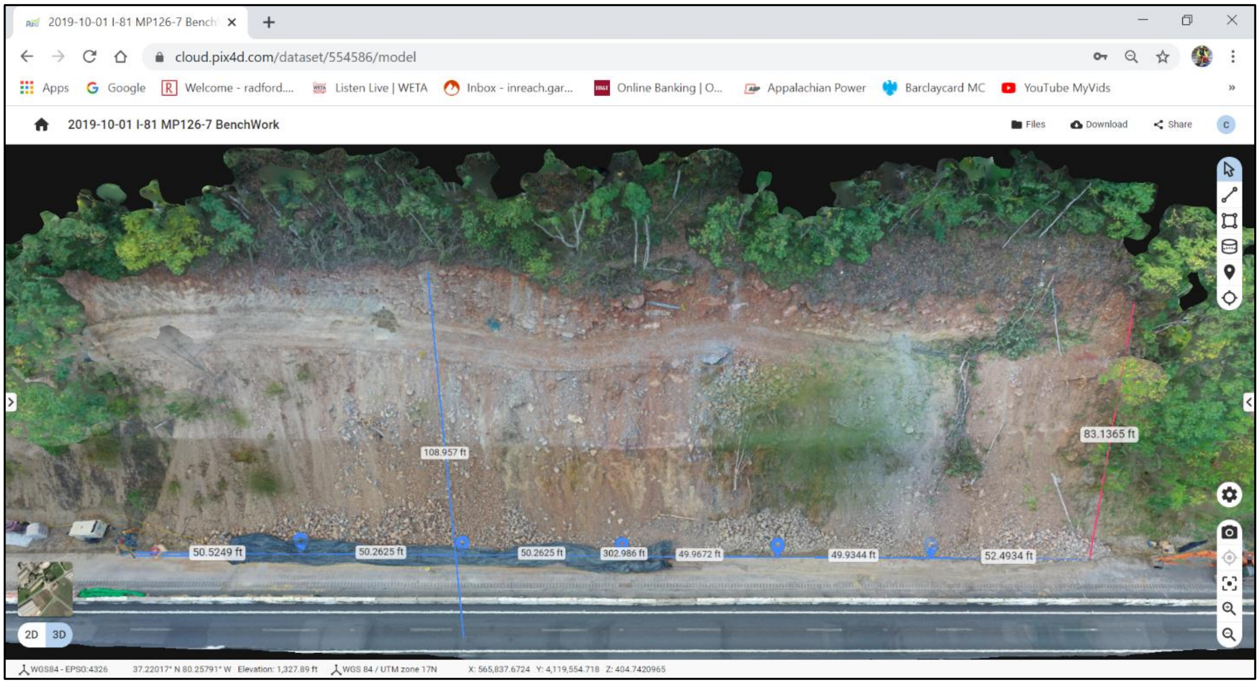

Figure 33. Site #6, Ironto, I-81 Milepost 126.7 Southbound. UAS demo project for GeoStabilization International illustrating the ability to monitor construction progress over time using dense point clouds and triangle mesh models generated in *Pix4D Cloud*.

Site #7 Processing - Salem Stone, ACCO Quarry, Blacksburg, and Holston Quarry, Dublin

<u>Site Factors</u>: Site #7a and 7b consist of highwalls located in the Salem Stone, ACCO Quarry, near Blacksburg, and the Holston Quarry, near Dublin. The ACCO Quarry is located immediately adjacent to the VTTI Smart Road. Major rock slope failures delayed construction of the Smart Road in 1998 and caused approximately $17 million in cost overruns. Geologic structural analyses and remediation strategies were developed at the request of Derek Whitehouse, State Highway Geologist, as part of Radford University graduate research by Robin Reed. The UAS stability analyses from the ACCO quarry are nearly identical to the traditionally-collected data from the 1998 study.

<u>Processing Options</u>: The following options were used to process imagery from Site 7a.

1. Aerial reconnaissance videos were captured and archived for comparison with rock slopes exposed during construction of the VTTI Smart Road (Figure 34a).
2. High resolution aerial photographs were selected and processed using *Pix4D Mapper* to create colorized point clouds and triangle mesh models along the entire slope (Figure 34b).
3. Computer-generated videos were made of the rock slope to animate the 3D model from moving perspectives, highlighting key features.
4. Geologic structure data in the form of discontinuity orientations were extracted from UAS point clouds using *CloudCompare* and *Split-FX* for comparison with traditionally-collected results from the nearby Virginia Tech Transportation Institute's Smart Road highway cut (Figure 35).

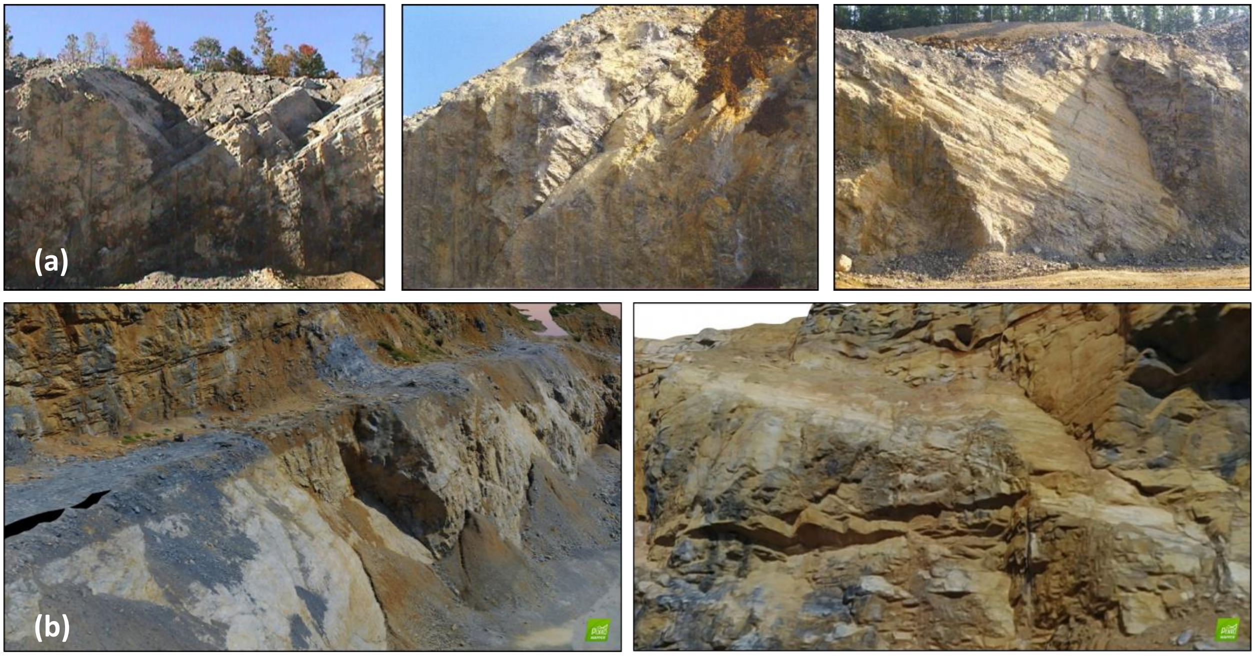

Figure 34. (a) Three photographs of unstable VTTI Smart Road rock slopes, adjacent to Site #7a, during construction in 1998. The geologic setting and structures are identical to those visible in the Site #7a UAS models. (b) Two UAS 3D triangle mesh models at Site #7a. Salem Stone ACCO Quarry adjacent to VTTI Smart Road.

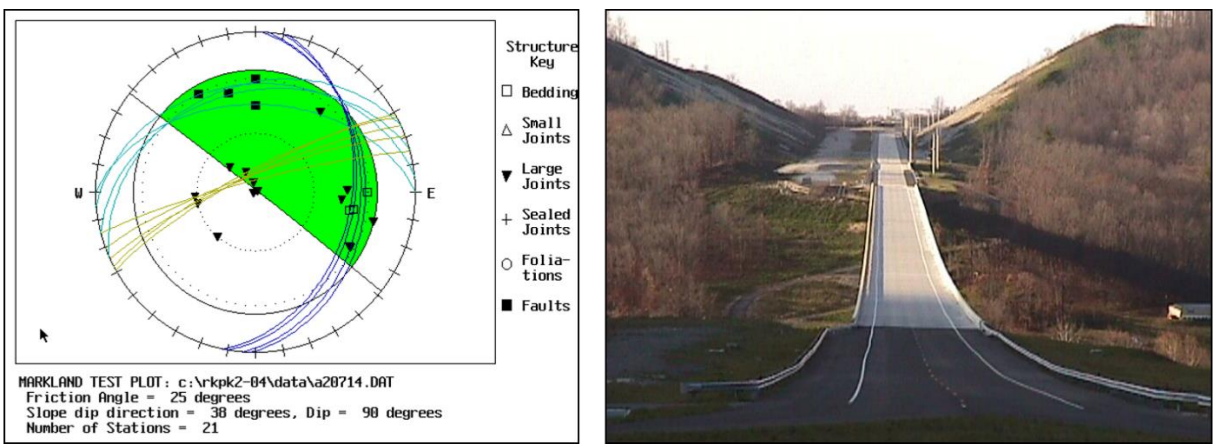

Figure 35. Stereonet derived from data collected manually in 1998 (left), comparable to 2019 UAS stereonets from the adjacent quarry. This plot reveals the cause of the unstable slopes (Figure 34a) during Smart Road construction, until laid back to 30 degrees as shown (right) at considerable cost overrun.

Task 9 - Perform 3D rockfall simulations

Three-dimensional rockfall simulations using the *Colorado Rockfall Simulation Program 3D* (*CRSP-3D*), in collaboration with the Federal Highway Administration (FHWA), were not performed as originally planned. The beta version of *CRSP-3D* is undergoing additional testing and revision by FHWA. Inclusion at this time would have been counterproductive. The prospect of working with it in the near future looks promising, however. Existing 2D rockfall simulation programs, although more limited, are good tools for predicting the travel paths, bounce heights, and kinetic energies of falling, rolling, and bounding rocks. That information is critical when designing rockfall diversions and barriers.

This research produced 3D UAS models suitable for both 3D and 2D rockfall simulations. Figure 36 shows Site #2, Deerfield, as an outstanding example of a location where rockfall simulations would be valuable. An earlier large rockslide occurred in the lower right corner of the point cloud image. Today, an active rockfall zone is seen in the center of the point cloud. Rocks falling onto the boulder field below the cliff face threaten a concrete anchor block, at road level, for guy wires supporting a power line tower at the top of the slope.

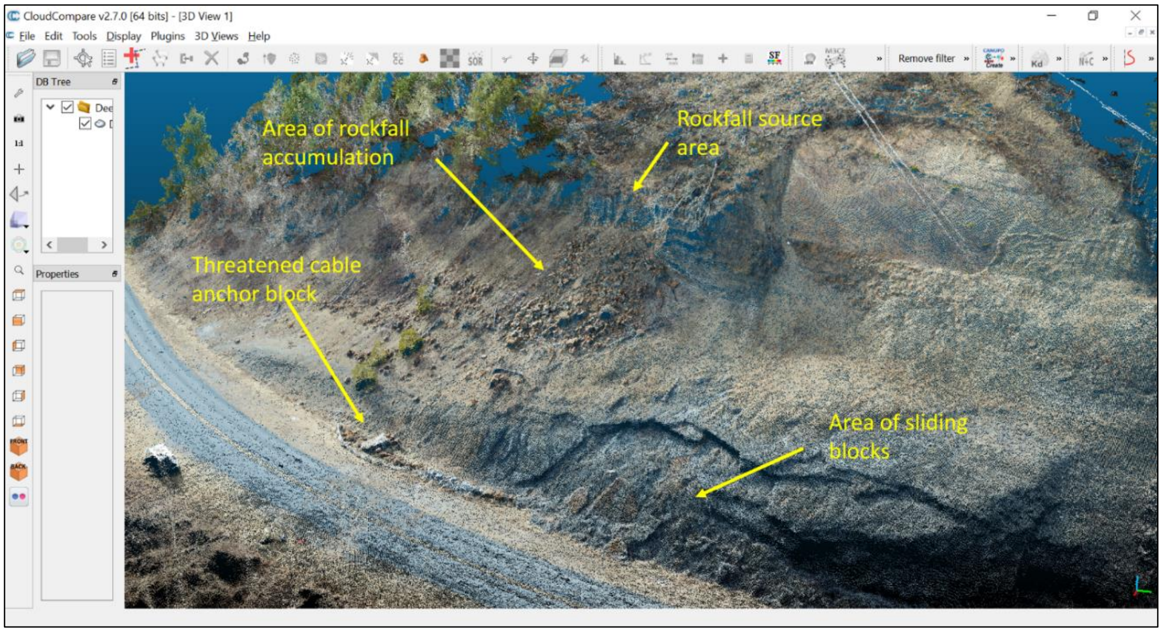

Figure 36. A digital point cloud for Site #2, flown in February of 2019, on Route 629 near Deerfield. An outstanding example of a location where 3D rockfall simulations, based on UAS imagery, would provide the data needed for design and remediation. Also, compare this image to the 2016 pre-failure point cloud (Figure 24), and the 2019 post-failure UAS photo (Figure 3), and the displacement heat map (Figure 38), illustrating where areas of movement over a 31-month period were detected by UAS change detection techniques.

Task 10 - Compare UAS results to standard traditional ground-based results

Site #2, Deerfield example

Task 6 examined the results of using traditionally collected data for rock slope design and mitigation purposes. Here we compare those results to the analysis of data collected by UAS. The Deerfield site serves as a good test site. It has been the focus of stability studies for over twenty years. A large rockslide occurred there in May of 2009. The site has been used as a natural rock slope laboratory ever since.

Data collected in 2016 using traditional compass methods and data collected by UAS during this study in 2019, were plotted on stereonets and compared to each other. Comparisons were made quantitatively by statistical analyses, including stereonet confidence cones, and visually by a careful inspection of the resulting stereonets.

Statistical Analysis of Discontinuity Orientation Data

The manually collected traditional transit compass data served as the control for evaluating the reliability of the UAS-collected data. For Deerfield, the statistics were calculated based on 362 transit compass readings. Those statistics were compared to 243 orientation readings extracted from the UAS data.

The computer program *DIPS* (RocScience) includes options for calculating a variety of statistical values for the PDSs (principal discontinuity sets). They include *variability limits*, *confidence limits*, and *Fisher's K values*. Looking specifically at the *variability limits*, they can be plotted as statistical cones on the stereonets. They appear as ellipses enclosing discontinuity clusters on the plots. *Confidence limits* for the clusters can also be plotted on stereonets and appear as small circles. High confidence in the UAS data would be indicated when the UAS confidence cones plot directly on top of, or very close to, the transit compass cones.

Figure 37 shows the *variability limits* cone plot for the transit compass data as well as for the UAS data. In these plots, the higher the degree of scatter for a given PDS, the larger the area of the variability cone. It is important to note that discontinuities are natural geologic structures within a rock mass and their orientations are expected to fluctuate normally within a given cluster. That provides greater statistical variability. For example, the bedding planes may be remarkably consistent at a given site, resulting in a small variability cone, whereas some joint sets might exhibit less consistency, resulting in a larger variability cone.

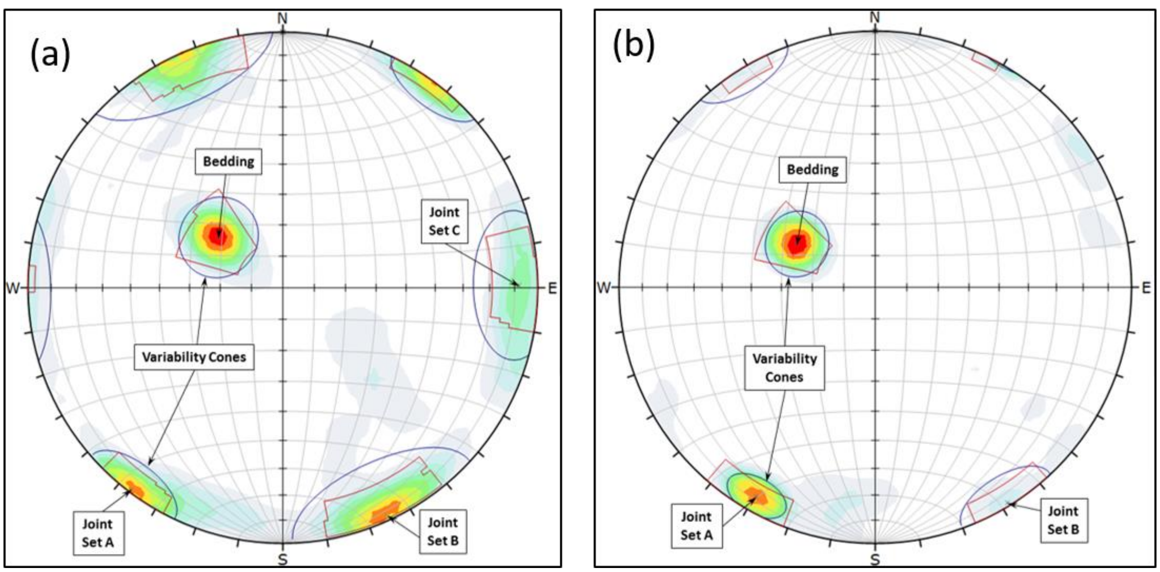

Figure 37. (a) Transit compass variability cone plot for principal discontinuity sets at Site #2 Deerfield. (b) UAS data variability cone plot for principal discontinuity sets derived from UAS data. The curved shapes around clusters represent the variability cones for the two data collection methods. The differences in positioning of the matching principal discontinuity sets are subtle. Transit compass data have more detail and the transit compass readings were not corrected for magnetic declination of -8.3 degrees.

The orientation statistics for this site appeared contradictory at first. Ambiguities were resolved when visual examination revealed that the manual compass readings had not been corrected for magnetic declination. This refers to the natural difference between magnetic compass readings and true compass directions which varies in value over time and location.

Apparent discrepancies are paraphrased from Delaney, et al. (2020) below, along with brief explanations of their resolutions:

(1) The variability cone plots (Figure 37) for the two methods show that the degree of scatter is reasonable. Joint set B exhibits higher scatter in the transit compass data and is less populated in the UAS data.

This aspect is to be expected and is inherent to the nature of the collection techniques. A person with ample experience, working at the rock face, is more likely to identify and include discontinuities that are smaller in size, than is an algorithm working with point cloud models developed using imagery taken from at least 100 feet away. The impact on design and mitigation is minimal because the smaller discontinuities have little to no control over global stability.

(2) The confidence cone plots of Delaney (2020) are not shown here to conserve space. However, they show that no cones intersect each other from the two methods. This suggests that, statistically, there is a lack of correlation between the traditional ground-based data and the UAS-based data collection methods.

The correlation issue between the transit compass and UAS-collected data is corrected by applying the appropriate magnetic declination of -8.3 degrees to the compass data. The dip angle values require no correction, as they correlate remarkably well, and would be expected since only the dip direction values require the magnetic correction.

(3) Fisher's K values are high enough to suggest that the principal discontinuities represented by these data sets have tight clusters and their identification should be reliable.

This confirms that the UAS data have reasonable precision, and that the accuracy was corrected by simply adjusting the transit compass data by the appropriate magnetic declination.

Visual Inspection Compared to Statistical Comparison

Visual inspection emphasizes the differences between precision and accuracy on the stereonets. Variability within the orientation clusters was reasonably small, indicating that the results were precise, even if the placement (accuracy) of the clusters appeared slightly off. Accuracy shifted to acceptable values once the standard correction for magnetic declination was applied.

It must also be noted that small discontinuities with less physical exposure tend to be less significant to overall stability and may be missed in the aerial data sets. Yet, they are likely to be seen and sampled by workers on the ground using traditional methods. For example, inspection of Figure 37 shows that the ground-based data captured four principal discontinuity sets (bedding, plus joint sets A, B, and C). On the other hand, the UAS data revealed only three principal discontinuity sets (bedding, plus joint sets A and B).

Safety Factor Comparisons for Traditionally Collected and UAS-Collected Data

Whenever kinematic stereonet analyses indicate that slope failures are likely, then safety factor calculations are called for. Safety factor calculations for the traditionally gathered data at the Deerfield site were reported in Task #6 to be 1.03, or barely stable, for both potential plane and wedge failures. The values were the same because the wedge geometry in this case results in sliding on only one of the surfaces forming the wedge. The other surface forming the wedge acts merely as a release surface.

For comparison, the safety factor calculations for the UAS-collected data at the Deerfield site are quite close to those for the transit compass-collected data. Using limiting equilibrium methods, the UAS data yielded a safety factor of 0.95, or barely unstable. The presence of both plane and wedge failures at the site (Figure 25) corroborates findings, from both traditional and UAS-based methods.

Task 11 - Test change detection software for slope monitoring

Change detection analysis based on UAS imagery shows great promise for monitoring rock slopes over time. As part of this investigation, point clouds were derived from older imagery collected in July of 2016 and from newer imagery collected in February of 2019. The point clouds were each gridded, matched, and differentiated on a pixel-by-pixel basis. Points known to be stable were correlated using *CloudCompare* software. The clouds were then merged to create the change detection heat map (Figure 38).

The inset graph depicts increasing displacement on the x-axis, versus numbers of pixels involved in movement on the y-axis. The red areas on the heat map indicate pixels of greatest change over the 31-month period while the blue areas indicate pixels of least change. This interpretation is confirmed visually by comparison with Figure 36. (Thomason et al., 2019).

Both Figure 36 and Figure 38 show a rockfall source area and an area of sliding rock blocks, represented in bright red in Figure 38. An area of rockfall accumulation is shown in a more neutral color. Stable areas are shown in bright blue. A red area near the top of the cut appears to represent changes in vegetation.

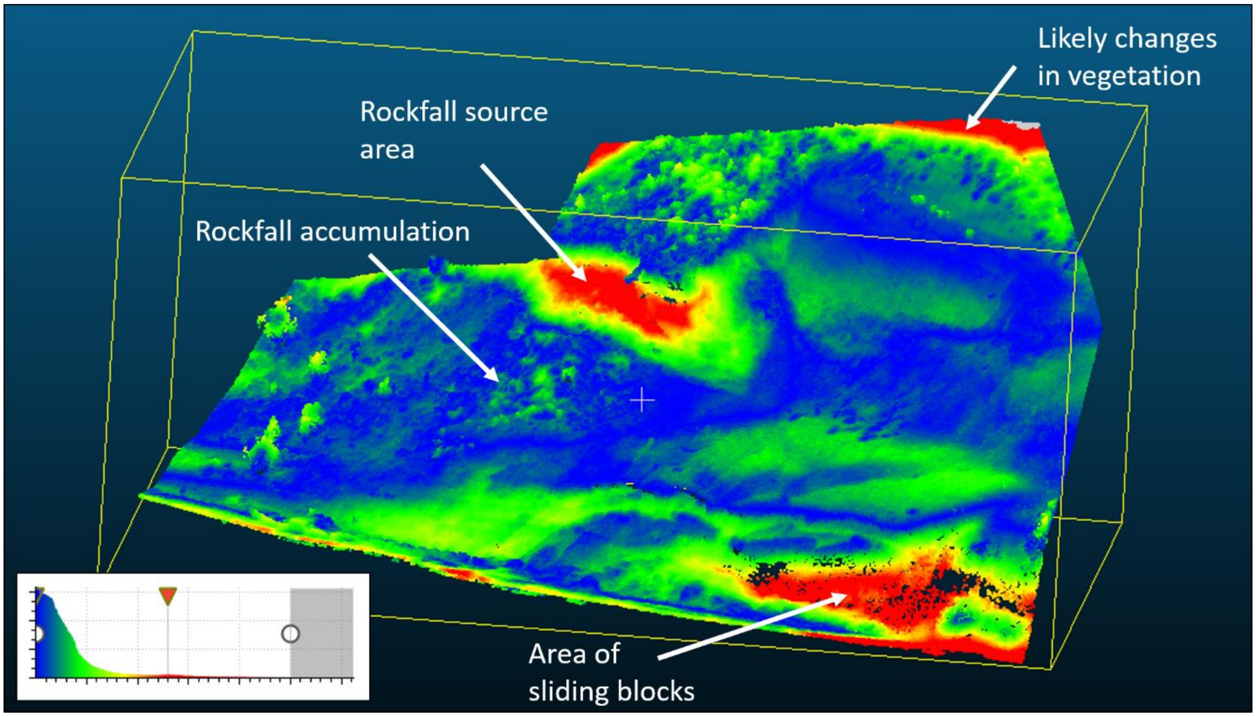

Figure 38. UAS change detection heat map for Site #2 Deerfield. Two point clouds were generated from UAS imagery collected in July 2016 and again in February 2019. The clouds were gridded, matched, and differentiated on a pixel by pixel basis. The red areas indicate pixels of greatest change over the 31-month period and the blue areas indicate pixels of least change. This interpretation is confirmed by comparison with Figure 36. From Thomason et al., 2019.

Task 12 - Evaluate cost-benefit and risk-rewards

Cost-benefit analyses for implementing UAS in the gathering of geologic data for rock slope design and mitigation along highways primarily involve the costs of (1) maintenance of traffic (MOT); (2) personnel time-on-task; and, (3) the benefits of increasing data quantity and quality using less time. The authors understand that a tool called HUB-CAP is available to VDOT for rigorous cost analysis of any delays associated with traveler congestion. That level of detail is outside the realm of our expertise. Some relevant comments are provided farther below.

Risk-reward analyses involve (1) evaluating risks to motorists encountering traditional roadside geotechnical investigations along the highway; (2) the safety of DOT personnel and contractors; and, (3) the rewards of implementing UAS data gathering techniques that enhance safety at lower cost. These too are outside the realm of our expertise.

Maintenance of Traffic

With regard to MOT on Interstate highways, geotechnical and geologic mapping of rock slopes may require a lane closure to protect ground-based workers collecting structure data for hours at a time. Lane closures could also be needed to protect motorists from rocks that might be dislodged, especially during investigations that require climbers to be on rock slopes. If there is significant risk, a temporary rockfall barrier would be called for. There are sites on I-81 where this would be the case. As one example, northbound near Greenville, dislodged material could roll under the guardrail and into the travel lanes.

Time and cost are significant. Personal communication with Brian Bruckno, VDOT Staunton District, indicates that the cost of a lane closure on a busy Interstate highway is high, regardless of cause. Most of the effort in MOT is setup and takedown, each requiring about an hour. Hence, there is little to no economy of scale for a short site visit to a rock slope requiring a lane closure. The use of UAS for data collection will, in most cases, prevent this.

At this time, we have no information pertaining to a shoulder closure compared to a lane closure. There are also costs associated with traffic backups or delays. Finally, MOT on Interstates is frequently limited to night hours, whereas UAS mapping is performed during daylight hours, weather permitting.

Time-on-task and Data Density

Traditional geologic structure mapping can be accomplished by one person. However, two people increase both the speed of mapping and the quantity of data collected. If rope access is required for data collection, a minimum of two people is required for safety while the time-on-task increases to an entire day or more.

Geologic structure mapping by UAS requires at least two people to meet FAA regulations, a remote pilot in command (RPIC) plus at least one visual observer (VO). A skilled UAS team can map large slopes in only a few hours, at the same time collecting some one to two orders of magnitude more of useable data, more safely, resulting in greater data density. In addition, FAA requirements are constantly evolving and may soon permit flying over live traffic.

In terms of cost per dataset, two geologists might obtain 300 data points using a transit compass on a good day. On the same day, geologists using UAS and 3D photogrammetry could easily obtain 3,000 data points. Assuming that the cost per day is similar for both traditional mapping and UAS mapping, the cost/benefit ratio is therefore improved at least 10-fold. The result is more data, collected more quickly and more safely. In other words, the overall costs are similar but data quality, quantity, and safety are all enhanced.

Risk-Reward Benefits

Safety is paramount. While difficult to quantify, geologic mapping along highways using UAS reduces risk and provides safety rewards in at least two basic ways. First, it minimizes the need for lane or shoulder closures during data collection, reducing the risk of traffic accidents and increasing safety for personnel in work zones. Second, it minimizes the need for geologists and engineers to place themselves in potentially hazardous conditions using rope access to acquire geologic data on slopes above road level.

Task 13 - Share results with stakeholders and implement best practices

This research has already generated keen interest from various stakeholder groups. Results and recommendations from this research are to be presented not only in this final report, but also at professional meetings, conferences, workshops, and short courses. A manuscript by graduate student Rachael Delaney, based on preliminary results, has been accepted for publication (Delaney, et al., 2020). It is anticipated that courses on UAS technologies applied to rock slope stability investigations will be presented through VDOT University (VDOTU). Results have been requested by the Rockfall Subcommittee of the Engineering Geology Committee of the Transportation

Research Board. Additional publications, presentations, and workshops covering implementation and best practices will be provided as appropriate. These will be in support of agencies, consulting firms, and contractors interested in applying these technologies. Results from this specific research have already been incorporated by HDR and GeoStabilization International for VDOT projects at Sites #4 and #6.

Summary of Findings

Five overall objectives were identified for this research as listed in the Purpose section. Eleven tasks were specified in order to meet those objectives. Each objective is discussed individually below.

1. Establish the methods, protocols, and workflow for safely using UAS for rock slope stability investigations along highways in accordance with federal, state, and local laws

Objective 1 is covered by Tasks 1, 2, 5, and 7

- Seven test sites were selected representing a variety of highway types and environmental conditions where slope stability issues have been a concern.
- An overall safety plan was developed and then tailored to fit specific circumstances at each site. Overall safety includes construction site safety, FAA and local rules and regulations, and lessons learned regarding safe flight operations.
- Operational safety includes proper rope access techniques for traditional data collection utilizing personnel trained in relevant mountaineering skills.
- Different types of flights were planned for each location to address site-specific goals, desired deliverables, and aircraft safety. Each project began with reconnaissance flights to capture site information from different perspectives and to identify challenges or aerial obstacles. Data collection flights consisted of manual “stick-and-rudder” slope scans or programmed autonomous flights as needed.
- Operational challenges included: working near moving traffic, tight airspace due to terrain, vegetation, and traffic; aircraft malfunctions and operator error; and vegetation cover limiting ground visibility during certain times of the year.

2. Test the accuracy of UAS mapping for specific rock slope applications using surveyed ground control points and least squares analysis.

Objective 2 is covered by Task 3.

- The use of manual tie points (MTPs) even without surveyed GPS coordinates for adjusting UAS-only derived coordinates enhanced the relative precision of features within the projects’ unique coordinate systems to values acceptable for geologic field mapping.
- This study utilized Emlid (brand) RTK and PPK GPS systems to obtain GCP coordinates. Root mean square (RMS) errors ranging from .337 meters (1.1 feet) to .099 meters (0.325 feet) were observed for the uncorrected UAS-only results above.
- The addition of surveyed GCPs increased the accuracy of map deliverables, within real-world coordinate systems, to inches of accuracy. While not considered accurate enough for highway design, these were more than sufficient for geologic field mapping where accuracies of plus and minus 2-degrees of angle and 0.5 feet in distance are expected.

3. Provide software recommendations and establish the workflow for extracting the geologic structure data needed for characterizing rock slopes to aid in slope design, remediation, and hazard inventories, from UAS 3D point clouds.

Objective 3 is covered by Tasks 4, 6, 8, 9, 10, and 11.

- The workflow for obtaining the structure data needed to aid in slope design, remediation, and hazard inventories involves the following steps: traditional mapping for comparison with UAS mapping and quality assurance; plotting discontinuity orientations on stereonets to check for possible slope failure modes; processing UAS data to produce 3D digital models; performing rockfall simulations in either 2D or 3D virtual spaces; comparing ground-based data with UAS-based results for confidence checking; and, performing change detection analyses if previous results are available to identify areas of greatest rockfall activity.
- Each step in the workflow can be performed or assisted using computer or smart device applications. While many exist, the following applications were found to work satisfactorily for completing the operations described below. This is not an endorsement of any particular applications over any other applications.
    - Manual data collection: *GeoID* for measuring and recording discontinuity orientations and performing field stability analyses
    - Stereonet plotting: *RockPack III* and/or *DIPS* for detailed kinematic stability analyses
    - Structure-from-motion processing: *Pix4D Mapper*, *Pix4D Cloud*, and/or *Photoscan* for generating dense point clouds, orthophoto mosaics, and topographic maps;
    - Map precision and accuracy testing using root mean square analysis: *Pix4D Mapper*;
    - Rockfall simulation modeling: *Colorado Rockfall Simulation Program* (CRSP) and/or *Rockfall*;
    - Extraction of discontinuity orientation data from point clouds: *CloudCompare* and/or *Split-FX*; and,
    - Change detection analysis: *CloudCompare*.
- The consequences of the loss of UAS-borne LiDAR data at the heavily vegetated #3 Lynchburg site are significant.
    - While SfM software, like *Pix4D*, does have the ability to strip vegetation and approximate bare earth models, it is not as accurate as LiDAR with its ability to parse point clouds for ground returns only. This is a limitation of photogrammetry at this time.
    - Nevertheless, photogrammetry is an order of magnitude less expensive, making it most practical for the majority of sites where rock slopes are bare and rock structures are well exposed.
    - UAS photogrammetry is becoming part of many geologists' standard tool kit along with compass, rock hammer, and tape.

4. Establish the workflow for using UAS point clouds for modeling of rockfalls using 3D applications like the Colorado Rockfall Simulation Program (CRSP), in collaboration with the Federal Highway Administration (FHWA).

Objective 4 is covered by Task 9.

- Rockfall modeling is an important part of rock slope design and mitigation. Slope profiles and/or point clouds make it possible to roll simulated rock blocks down real-world slopes.

The simulations provide estimations of travel distances, travel paths, bounce heights, and kinetic energies.

- Such information is invaluable when reshaping existing slopes to make them safer, constructing catchment benches or ditches, and designing rockfall fences and barriers.
- The workflow, using UAS, involves flying missions planned to capture overlapping oblique aerial photos of the slope; processing imagery using structure-from-motion applications to create a scaled point cloud representing the slope; generating 2D profiles of the slope face from the point cloud for running original CRSP (2D) simulations; or generating 3D models used to run CRSP 3D, possibly allowing for more accurate predictions of rockfall behavior in 3D space.
- Models suitable for use in both CRSP and CRSP 3D were produced as part of this research. 2D profiles were extracted from the point clouds that were satisfactory for CRSP modeling. The 3D point clouds were also suitable for use in CRSP 3D modeling, however, planned testing in collaboration with FHWA did not materialize. The CRSP 3D software continues to have programming issues as of this writing.

5. **Test the use of change detection software for quantifying slope changes using UAS point clouds.**

Objective 5 is covered by Task 11.

- Change detection is a useful aspect of rock slope design and mitigation. If multiple missions are flown over time, digital models can be superimposed, one on another, and compared to identify temporal changes in slope geometries.
- Changes in slope geometry detected in this manner will indicate areas of greatest rockfall or rockslide activity that are often more difficult to identify and track from maintenance records alone.
- Change detection analyses were successful for the #2 Deerfield site when comparing digital models created from imagery captured in 2016 with imagery captured in 2019. While the analyses clearly showed areas of greatest activity over time, additional study is needed to extrapolate these results over additional sites.

CONCLUSIONS

1. *UAS-derived data are equal to or superior to traditional ground-based transit compass and tape measure data for the geologic mapping of rock mass discontinuities in terms of precision, accuracy, data density, and efficiency.*

2. *The use of UAS for gathering the geological and geotechnical information needed to design slope configurations and mitigations for potentially hazardous rock slopes is highly and immediately implementable, while offering benefits in both cost and safety.*

3. *Unmanned Aerial Systems can be used in accordance with federal, state, and local laws to safely and efficiently investigate rock slopes for safety and stability. Methods, protocols, and workflow steps were established and used at seven sites spread across Virginia.*

4. *Unmanned Aerial Systems mapping, used for rock slope design, risk analysis, and hazard mitigation, proved to be as accurate, or more, and as useful, or more, compared to traditional*

data collection methods. Root mean square error analyses of accuracy, within global coordinate systems, were as low as 0.099 meters (0.325 feet), when tested against RTK and PPK GPS survey equipment. This is of greater accuracy than traditional geologic structure mapping.

5. *The workflow for extracting geologic structure data for characterizing rock slopes, to aid in slope design, remediation, and hazard inventories, is well documented. Various computer and smart device software applications are available to assist in this task. A list of applications that produced satisfactory results is provided in the report body.*

6. *The loss of UAS-borne LiDAR data at heavily vegetated sites is significant. Nevertheless, photogrammetry is a viable alternative. SfM software is evolving and is gaining the ability to strip vegetation and approximate bare earth models. Photogrammetry is far less expensive, making it most practical for the majority of sites where rock slopes are bare and rock structures are well exposed.*

7. *The workflow for manipulating point clouds to model rockfalls, including those derived from UAS imagery, with software like the Colorado Rockfall Simulation Program (CRSP) is also well documented. Such analyses are critical when configuring rock slopes in ways to minimize danger from falling rock to the traveling public and when designing rockfall fences and barriers.*

8. *Change detection software was found to be useful for identifying areas of greater rockfall activity across the slope at Deerfield over a three-year period. Additional study is needed to extrapolate this finding to other sites. These results suggest this to be a valuable tool as hazardous rockfall areas are not always evident from maintenance records alone.*

RECOMMENDATIONS

1. *VDOT's Geotechnical Engineering Program (Materials Division) should consider the implementation of UAS for routine gathering of geologic structure data relevant to the configuration, design, mitigation, and inventory of rock slopes.*

2. *UAS operations for rock slope stability studies should be performed in accordance with the VDOT Unmanned Aerial Systems (UAS) Operations Manual, issued by the Location & Design Division in January, 2021.*

   Note: The VDOT UAS Operations Manual was first issued in 2021 as this Radford University research was nearing completion.

   Section 1.0 states: *This manual applies to all UAS operations for all VDOT activities, both construction and maintenance, administered by VDOT and performed either by its internal workforce or contracted to external entities, excluding Design Build (DB) projects. For any DB project, it is the responsibility of the DB Team to ensure compliance with all local, state, and federal requirements as well as ensure use of UAS is appropriate and valid. As such, VDOT assumes the elements of the manual or equivalent are being followed for any DB project.*

IMPLEMENTATION AND BENEFITS

Implementation

Regarding Recommendation 1, a task group of representatives from VDOT's Geotechnical Engineering and GeoSpatial Programs will use the findings from this report to develop (or have developed) documented procedures to incorporate unmanned aerial systems into its workflow for gathering geologic structure data relevant to the configuration, design, mitigation and inventory of rock slopes. This recommendation will be implemented within the first six months of 2022.

Regarding Recommendation 2, a task group led by VDOT's GeoSpatial Program and in concert with Geotechnical Engineering, Administrative Services, and others as needed will develop the recommended criteria. This recommendation will be implemented by the end of 2022.

Benefits

The benefits of implementing UAS for gathering and processing digital imagery relevant to the configuration, design, mitigation, and inventory of rock slopes include:

1. Rapid collection of geologic structure data necessary for analyzing the stability and safety of existing or proposed rock slopes and for the configuration design and remediation of unsafe rock slopes.

2. "Eyes in the sky," providing rapid, cost effective, aerial reconnaissance and useful visuals from perspectives not normally available and providing for the prompt identification of rock slopes that pose some risk to VDOT personnel, infrastructure, and the traveling public.

3. Assisting in the design of the most effective remediation options, including slope reconstruction, rockfall fences and barriers, or catchment maintenance, using metrics extracted from 3D digital models.

4. Provide digital models for identifying slopes with long rock fall rollout distances, using applications such as FHWA's *CRSP* or RocScience's *RocFall*.

5. Provide slope data for a possible inventory of hazardous rock slopes and to assess their associated hazard ratings in collaboration with Dr. Yonathan Admassu of James Madison University, another VTRC researcher.

6. Provide greater efficiency, cost benefits, and worker safety while investigating, collecting geologic structure data, and designing new rock cuts, or, while remediating existing hazardous rock slopes.

7. Offer the potential to expand some these methodologies to other assets including bridge abutments, bridge piers and scour, tunnels, and tunnel portals.

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REFERENCES

Badger, R.L., and Sinha, A.K. Geochemical Stratigraphy and Petrogenesis of the Catoctin Volcanic Provence, Central Appalachians. In *Proterozoic Tectonic Evolution of the Grenville Orogen in North America*, Tollo, R.P., Corriveau, L, McLelland, J., and Bartholomew, M.J. (Eds.). Boulder, Colorado, Geological Society of America Memoir 197, 2004, pp. 435-458.

Brown, W.R. Geology and Mineral Resources of the Lynchburg Quadrangle, Virginia. *Virginia Division of Geology and Mineral Resources Bulletin* 74, 1958, 99 p.

Carter, M.W., Southworth, S., Tollo, R.P., Merschat, A.J., Wagner, S., Lazor, A., and Aleinikoff, J.N. Geology along the Blue Ridge Parkway in Virginia. In *From the Blue Ridge to the Beach: Geological Field Excursions across Virginia*. Bailey, C.M., and Jaye, S. (Eds.), Boulder, Colorado, Geological Society of America Field Guide 47, 2017, pp. 1-58.

Delaney, R.K., Shakoor, A., and Watts, C.F. Evaluating the Use of Unmanned Aerial Systems (UAS) for Collecting Discontinuity Orientation Data for Rock Slope Stability Analysis. *Environmental & Engineering Geoscience*, 2020, in press.

Henika, W.S. *Geologic Map of the Ironto 7.5-minute Quadrangle, Virginia*. Virginia Division of Geology and Mineral Resources, 2010 STATEMAP Deliverable, 1:24:000-scale geologic map.

McDowell, R.C., and Schultz, A.P. *Structural and Stratigraphic Framework of the Giles County Area, a Part of the Appalachian Basin of Virginia and West Virginia*. U.S. Geological Survey Bulletin 1839-E, 1990, 24 p.

Neiman, W. Use of Digital Photogrammetry to Monitor Change at Selected Rock Slopes. *Virginia Center for Transportation Innovation & Research*: Marshall Proposal 237, 2011, p. 14.

Rader, E., and Wilkes, G. *Geologic Map of the Virginia Portion of the Staunton 30 X 60-minute Quadrangle*. Virginia Division of Mineral Resources Publication 163, 2001.

Rankin, D.W., Espenshade, G.H., and Shaw, K.W. Stratigraphy and Structure of the Metamorphic Belt in Northwestern North Carolina and Southwestern Virginia: A Study from the Brevard Fault Zone to the Sauratown Mountains Anticlinorium. *American Journal of Science*, Vol 273-A, 1973, pp. 1-40.

Reed, R.E., and Watts, C.F. *Smart Road Deep Cut: Inventory of Problematic Areas with Regard to Rock Slope Stability as of August 1998*. Memorandum Report to Derek Whitehouse, Virginia Department of Transportation, 1998.

Reed, R.E. *Rock Slope Stability of the Smart Road Rock Cut in Blacksburg, Virginia*. [M.S. Thesis] Radford, Virginia, Radford University, 2003.

ROCSCIENCE. Dips software (version 7.0), 2020. https://www.rocscience.com/software/dips. Accessed September 24, 2020.

Southworth, S., and Brezinski, D.K. *Geology of the Harpers Ferry Quadrangle, Virginia, Maryland, and West Virginia*. U.S. Geological Survey Bulletin 2123, 1996, 33 p.

Thomason, A.R., Farmer, S.L., Watts, C.F., and Stephenson, G.C. Using Unmanned Aerial Systems (UAS) to Produce Point Clouds of Quarry Walls for Testing Change Detection Software and their Application to Studying Highway Rockfall Rates. *Geological Society of America* Abstracts *with Programs*, Vol. 51, No. 3, 2019. doi: 10.1130/abs/2019SE-327839.

U.S. Geological Survey. Geologic Units in Lynchburg City, Virginia. https://mrdata.usgs.gov/geology/state/fips-unit.php?code=f51680. Accessed March 15, 2020.

VDOT Governance Document. *Unmanned Aerial Systems (UAS) Operations Manual*. Virginia Department of Transportation, Location & Design Division, January 2021.

Watts, C.F., and Whisonant, R.C. *Afton Mountain, Evaluation of Slope Stability and Recommendations*. Project 02-0064-7089, Virginia Department of Transportation, 1988, 113 p.

Watts, C.F. User's Manual, RockPack III for Windows, Rock Slope Stability Computerized Analysis Package, Part One – Stereonet Analysis. C.F. Watts & Associates, 2003.

Whisonant, R.C., and Watts, C.F. Using Dip Vectors to Analyze Structural Data, *Journal of Geological Education*, Vol. 37, No. 3, 1989, pp. 187-189. doi: 10.5408/0022-1368-37.3.187.

APPENDIX

OVERVIEW OF FAA RULES AND REGULATIONS REGARDING COMMERCIAL UAS OPERATIONS

Establishing an unmanned aerial systems (UAS) group within a larger organization involves mastering three distinct elements, all of equal importance, each with its own set of learning curves. Successful UAS operations require an investment of time and money. The three elements are:

1. Federal Regulations - understanding and meeting Federal Aviation Administration (FAA) requirements for remote pilot certifications and for aircraft registrations. Both are required by law for commercial and government UAS programs.

2. Flight Operations - managing pilot flight training, physically maintaining aircraft, updating aircraft firmware and software, updating flight control software, and tracking insurance needs.

3. Image Data Processing - downloading and storing large datasets, processing data to generate deliverables, including reconnaissance videos, 3D computer models, and georeferenced maps including GIS layers and orthophotomosaics.

This appendix provides an overview and links to resources for only the first element, Federal Regulations. Meeting FAA regulations entails three steps: (1) study and learn federal, state, and local regulations; (2) pass the FAA Part 107 exam to obtain certifications as Remote Pilots in Command (RPICs); and, (3) register all unmanned aerial vehicles (UAVs) with the FAA.

The website https://www.faa.gov/uas/ provides all necessary information regarding training and steps to certification. Free online tutorials, as well as commercial online and in-person training are available through third party vendors found on the Internet. Regardless of the training method, one should be prepared to spend several days to a few weeks studying, preparing and practicing in order to adequately prepare for the FAA exam.

The two most important training documents are:

The FAA Part 107 Remote Pilot Study Guide:
https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/media/remote_pilot_study_guide.pdf

The FAA Test Supplement, provided by the test proctor as a reference during the exam:
https://www.faa.gov/training_testing/testing/supplements/media/sport_rec_private_akts.pdf

All FAA knowledge tests are administered at FAA-designated computer testing centers operated by PSI. Testing centers can be located at https://faa.psiexams.com/faa/login.

Overview of FAA Commercial Rules and Regulations regarding the use of UAS

Step 1: Become familiar with CFR 14 Part 107 rules, including the following few examples: see www.faa.gov/uas/media/part_107_summary.pdf

- Applies to unmanned aerial vehicles (UAVs) greater than 0.55lbs and less than 55 lbs.
- Must have an FAA Certified Remote Pilot in Command, on site and near the controls
- UAV remain within visual line of sight (VLOS)
- UAV must not fly over people who are not flight crew members
- Cannot fly higher than 400 feet above ground level (AGL)
- Only daylight flights are allowed without a separate certificate of waiver (COW)
- Must not fly within 5 miles of any airport without authorization

Step 2: Obtain FAA remote pilot certifications: go to https://www.faa.gov/uas/commercial_operators/become_a_drone_pilot/

- Must be at least 16 years old
- Obtain an FAA Tracking Number (FTN)
- Schedule an appointment with a Knowledge Testing Center
- Pass the Aeronautical Knowledge Test
- Complete FAA Form 8710-13 to receive the Remote Pilot Certificate

Step 3: Register each of your organization's UAVs with the FAA: see link https://faadronezone.faa.gov/#/, and select *Fly sUAS under Part 107*

- Fill in the required data, and be ready to pay the $5 fee that is good for 3 years
- The registration number must be applied to a visible location on all UAVs

Conclusion: Follow all FAA Rules and Regulations. The FAA is a safety-oriented organization constantly developing new guidelines and modifying regulations. Visit https://www.faa.gov/uas/ often. Organizations should designate one or more employees to the task of monitoring UAS rules and regulations as they pertain to UAS applications within the organization.