November 2023 | FHWA-HIF-23-069

Tech Brief

USE OF UNMANNED AIRCRAFT SYSTEMS FOR EARTH MOVEMENTS

INTRODUCTION

This document provides information to support Unmanned Aircraft Systems (UAS) integration for detecting and monitoring earth movements. These systems may be used for many earth movement applications such as rockfall monitoring, landslide deformation analysis, post-earthquake ground deformations, and general emergency response. In many applications, change analyses are conducted through repeat surveys with UAS.

Without UAS, monitoring typically relies on either coarser airborne or satellite information (e.g., imagery or Interferometric Synthetic Aperture Radar) or ground-based methods such as Light Detection and Ranging (LiDAR) or robotic total stations. UAS platforms can be attractive for these applications because they provide a cost-effective, versatile, flexible, and rapid three-dimensional (3D) mapping approach. The speed and versatility of the platform is particularly important for monitoring earth movements in a dynamic environment. In some immediate response applications, ground movements do not allow sufficient time to conduct more traditional ground-based surveys and can pose safety risks. Hence, UAS technology could be suited to fill in this gap and may also be effective in longer-term monitoring programs.

FEDERAL AVIATION ADMINSTRATION REGULATIONS

UAS operators in both the public and private sectors must also adhere to statutory and regulatory requirements. Public aircraft operations (including UAS operations) are governed under the statutory requirements for public aircraft established in 49 USC § 40102 and § 40125. Additionally, both public and civil UAS operators may operate under the regulations promulgated by the Federal Aviation Administration (FAA). The provisions of 14 CFR part 107 apply to most operations of UAS weighing less than 55 lbs. Operators of UAS weighing greater than 55 lbs may request exemptions to the airworthiness requirements of 14 CFR part 91 pursuant to 49 USC §44807. UAS operators should also be aware of the requirements of the airspace in which they wish to fly as well as the requirements for the remote identification of unmanned aircraft. The FAA provides extensive resources and information to help guide UAS operators in determining which laws, rules, and regulations apply to a particular UAS operation. For more information, please see https://www.faa.gov/uas/

BENEFITS AND CHALLENGES

UAS technology may offer multiple benefits when monitoring earth movements compared with other alternatives, including:

- **Safety**
    - Earth movements tend to occur in steep, mountainous or hilly regions where space for conventional ground-based surveys is limited. These movements also disrupt survey control.

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    - Terrain susceptible to earth movements is often rugged and difficult to walk on because of frequent movement, which makes it challenging for crews with bulky survey equipment to acquire conventional measurements. With UAS, data may be collected across the landslide with relative ease as crews may avoid traversing the terrain in many cases. Note that some access may still be needed to set ground control points (GCPs), but these can often be placed strategically in more accessible locales.
    - Crews could be located in a safe location farther away from the slope, away from falling rocks, deep tension cracks, and other hazards.
    - Crews would be able to operate away from the roadway, which is particularly important given that landslides could result in access limitations on roadways including rough roads, cracking, rutting, and other pavement distresses.
- **Versatility**
    - UAS could be an effective tool to analyze a wide range of sites ranging from small slope failures to slopes along corridors several miles long.
    - UAS platforms can support several sensors, including red, green, and blue (RGB) cameras, LiDAR, and hyperspectral images that may be helpful for characterizing the morphology and geology of a site.
- **Productivity**
    - UAS platforms may efficiently cover a large site compared with ground-based solutions.
    - UAS platforms could allow the terrain to be viewed efficiently from multiple vantage points, enabling effective coverage across the site. While Structure from Motion (SfM)/Multi-view Stereo (MVS) photogrammetric techniques cannot see through dense vegetation to acquire terrain, some effects of vegetation blockage can be mitigated by flying the UAS to acquire data behind a tree or bush to help in areas of light to moderate vegetation that are often blocked from road-based, ground LiDAR surveys of steep slopes.
    - The ability to meticulously plan the flight path (e.g., height, speed, overlap) could result in more uniform data across the site compared with ground-based LiDAR, which is helpful for generating accurate Digital Terrain Models (DTM)s and performing analyses.
- **Flexibility**
    - The lightweight nature of UAS may enable them to be easily deployed in an emergency situation or in response to a hazardous event.
- **Reliability**
    - Setting conventional GCPs that are stable for reference marks can be challenging. UAS could use real-time kinematic/post-processing kinematic (RTK/PPK) global navigation satellite system (GNSS) solutions for direct georeferencing which would minimize the need for GCPs.

Challenges and considerations when operating UAS in these environments include:

- Operating UAS in steep terrain can be challenging. Some of these issues may be mitigated with terrain-following piloting software; however, extra care should be taken on steep terrain with tall vegetation, particularly in narrow canyons.
- RTK/PPK positioning capabilities may be needed when monitoring earth movements because access to place GCPs at these sites is often limited. Additionally, given the unstable nature of the terrain, it can be difficult to set reliable, long-term reference points for GCPs.
- UAS usage close to the highway may cause driving distractions (Barlow et al. 2019), which could be especially hazardous when operating on steep, mountainous roads.
- Conflicts can arise with manned aircraft operations for emergency response efforts that may not allow the use of UAS in the area of interest.

- In many cases, landslide/rockfall sites are remote, and cell/data connections may not be available for uploading UAS data or transmitting other information from the field.
- Given the rugged, windy, steep terrain, it could be difficult to maintain line of sight with the UAS; multiple operation locations may be needed. In addition, finding suitable take-off/landing locations can be challenging given the ruggedness of the terrain and vegetation.
- Wildlife (particularly birds) may feel threatened by the aircraft and react in a way that poses additional challenges.
- Weather hazards (snow, rain, and strong winds) common to mountainous terrain could substantially limit windows of operation.
- Maintaining the stability necessary for high-quality images without blurring can be difficult with adverse conditions common in canyons (e.g., winds, rain, snow).

PROCEDURES

This section summarizes common data collection and processing procedures and protocols found in use at State DOTs (Federal Highway Administration, 2018).

DATA COLLECTION OPERATIONS

When monitoring earth movements over time or responding to them, the following should be considered:

- Identify locations of stable ground control
- Determine the frequency of surveys of the earth movement area of interest
- Determine the number and distribution of GCPs.

The data collection plan can then be designed to ensure project specifications are satisfied. Data collection mission parameters such as acquisition height, image overlap settings, camera angles for data collection, and flight line patterns may be determined using mapping planning software which could significantly influence the resulting project accuracy.

Other factors to be considered when planning the survey may include (1) take-off/landing point and flying height, (2) the overlap between flight lines (higher in vegetated areas), (3) the speed of acquisition (which affects resolution), (4) sensor characteristics, (5) inaccessible areas, and (6) topography, which is often complex and variable in the case of a landslide which by nature disrupts terrain. Maintaining a constant flight height may be difficult and ultimately could affect the ground resolution as the topography changes. Depending on the changes in topography, in some cases it may be advantageous to fly parallel to the slope and work upward, while in others it may be better to fly perpendicular. It may be helpful to consider having some flightlines intersect at 90-degree angles to validate the calibration of the Inertial Navigation System. Figure 1 provides an example of a data mission layout plan.

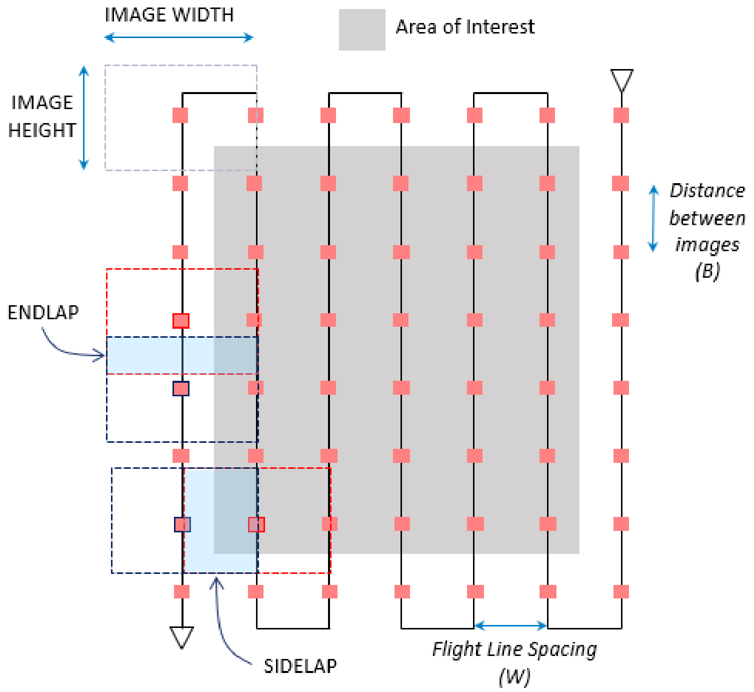

Figure 1. Example data mission layout (Source: FHWA)

Once the general flight path is established, a more detailed analysis of expected ground-sampling distance (GSD) (GSD, pixel size or spacing between LiDAR points) can be obtained from the flight lines to optimize the flying geometry. Flight altitude is one of the most influential factors affecting the quality of the end product. Overlap settings (front and side overlap) and the orientation for best data capture should be determined. A DTM is necessary to obtain a more accurate estimate. GSD is a function of the flying height, flightline configuration, sensor characteristics, and speed. In addition, when estimating the point density from LiDAR scans, it may be helpful to consider that the GSD is not representative of actual ground points because the analysis does not account for vegetation.

When designing the flight lines, it may be helpful to capture a larger area than needed to provide some data in “stable” locations next to a landslide so that change detection results can be validated and biases between surveys can be determined. In addition to be distributed throughout the area, GCPs should be placed to bound the survey area. However, GCPs placed at the edges of the surveyed area may not be well-captured.

EARTH MOVEMENT ANALYSES USE CASES

ROCKFALLS

UAS technology may be beneficial in analyzing rockfall activity and stability of rock slopes. Applications could include:

- Obtaining the big picture and localized detail of geomorphic processes (e.g., fracturing, weathering).
- Computing the rockfall activity index (RAI) (Dunham et al. 2017) to characterize the slope morphology and identify areas with highest risk.
- Performing change detection and monitoring of the rock slope.
- Computing volumes of rockfalls, identifying clusters, and creating magnitude frequency relationships to quantity and compare risk between rock slope segments.

Use of UAS technology for remote surveying of rock slopes may have advantages over conventional methods. First, UAS can have safety benefits over inspectors gathering information while climbing slopes to investigate issues. Next, the detailed point clouds and image analysis from UAS could provide quantitative, systematic data compared with conventional rockfall hazard rating systems, where results may vary from inspector to inspector. Lastly, the flexibility of the viewpoint of the UAS may improve cliff views compared with terrestrial or mobile laser scanning, especially on benches, on the upper sections of slope that result in data gaps.

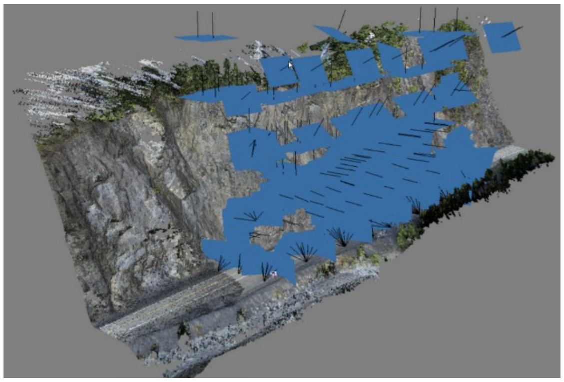

Figure 2. Figure of a SfM/MVS-derived point cloud of a rock slope on the Glenn Highway in Alaska. Camera location, orientations, and focal planes for each image are shown. Image Source: O'Banion et al., 2018

O'Banion et al. (2018) performed a detailed comparison of UAS-SfM/MVS data to terrestrial LiDAR for several rock slope sites along the Glenn Highway in Alaska (Figure 2). In this study, the UAS was flown in manual mode to capture images from multiple vantage points. Note the unstructured nature of the photograph acquisition due to the lack of flight planning software to support auto image acquisition for vertical features at the time of survey. In comparison to the terrestrial LiDAR data, the following observations were made:

- Sharp edges from rock discontinuities were rounded and smoothed compared with LiDAR data.
- UAS SfM outperformed LiDAR for seeing beneath and behind sparse vegetation.
- In dense ground cover/vegetation, LiDAR outperformed drone SfM (active vs. passive light source).
- Many artifacts were observed in boundaries of SfM model.
- Survey control targets were placed across the scene; however, they could only be placed at the bottom of the cliff due to accessibility constraints and safety reasons. This resulted in error propagation and drifting of some models toward the top of the cliff.
- The errors in SfM depended on the distance, quality of texture for key point matching, lighting conditions, and quality of GCPs.

In research for the Pacific Northwest Transportation Consortium (PacTrans) and the Oregon Department of Transportation (ODOT), Olsen et al. investigated the suitability of UAS technology for change detection of rock slopes (Olsen et al. 2021). Figure 3 shows some example data products from this investigation, including a clustering analysis to identify individual rockfall features between two epochs of data completed in a processing software (Olsen et al. 2021). The volume of each rockfall cluster can be computed, and a magnitude frequency curve can be generated such as those shown in the right plot. Magnitude frequency curves relate the hazard between sites and show the distribution of how often small rockfall events vs. large rockfall events happen at a site as well as the overall amount of rockfall happening at the site (i.e., as the curves move upward, they show increased activity at the site). These magnitude frequency curves follow a power law relationship.

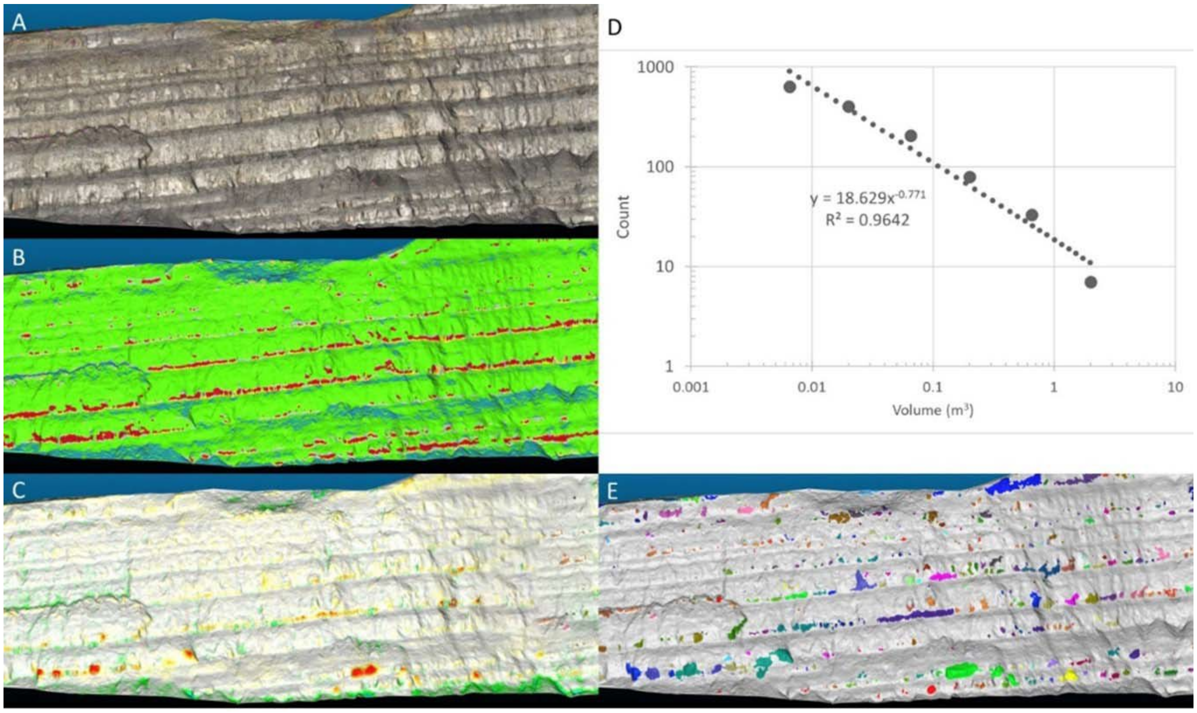

Figure 3. Example UAS-SfM/MVS geomorphological analysis for a rock slope in Eddyville, Oregon. (A) RGB photographic information texture mapped to a digital terrain model. (B) RAI morphological analysis showing areas of overhang, talus and intact rock. (C) Change detection analysis results. (D) Magnitude frequency relationship showing the distribution of rockfalls based on volume. (E) Individual rockfall cluster analysis for developing the magnitude frequency distributions. Image Source: Oregon State University

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TAKEAWAYS

Oregon State University (OSU) and the Oregon DOT learned the following from using UAS technology for rock slope assessment:

- Many flight planning software packages may not be reliable for vertical, complex topography such as rock slopes. For these situations the UAS can be operated in manual mode. (Some software does allow for developing flight plans for towers – cylindrical or rectangular objects.)
- Generally, targets for SfM reconstruction can only be safely placed at the base of the cliff, which can lead to error propagation of the surface reconstruction with SfM/MVS algorithms toward the top of the slope.
- Acquisition of ground photos can complement the UAS photographs (e.g., higher resolution camera, better captured targets) and significantly improve results. In particular, the ground-based photographs can often capture the base and top of the rock outcrop within the same photograph, limiting drift issues discussed in the previous bullet.
- With adequate survey control and careful processing, SfM/MVS can approach the accuracy of terrestrial LiDAR for rock slope assessments.
- SfM/MVS can provide higher resolution results compared with terrestrial LiDAR and provide a more uniform point distribution on the surface. The platform flexibility also reduces data gaps by allowing data to be captured from multiple perspectives and vantage points.

LANDSLIDES

UAS technology may support a variety of applications for landslide assessment, including identifying landslide features (e.g., scarp, debris, extents/boundaries, tension cracks, damaged structures); change analysis between epochs; and tracking movements across an active flow slide.

Babbel et al. (2019) explored the use of UAS LiDAR to investigate the Spangler Landslide in Molalla, Oregon. The change analysis (Figure 4) of the UAS LiDAR DEM (Digital Elevation Model) was performed with respect to an airborne laser scanning (ALS) data set collected in 2009 by the Oregon LiDAR Consortium and yielded several important observations regarding the landslide. First, a graben is apparent from the change detection results (represented as a red section [subsidence] traversing the road). A graben is a block that subsides at the head of a landslide, wedged between the landslide body and headscarp. Thus, the vertical settlement is notable at the head of the landslide. The road appears as accretion (blue) as a result of repaving and reconstruction at the onset of slope failure. Second, throughout the landslide body, a region of accretion (i.e., heave/advance) is observed, represented in blue. The observed accretion from change detection occurs as the generally translational movements of the landslide body, resulting in an apparent increase in the elevation of the downslope embankment. Third, most of the displacement is occurring at the northwest portion of the slide, likely due to increased groundwater levels from a recently installed pond at the bench, west of the headscarp. Lastly, the DEM highlights numerous similar failures within the overall landslide complex. The current failure zone is likely the next calving block from a loss of lateral support from adjacent failures to the northwest as well as a relatively high ground water table.

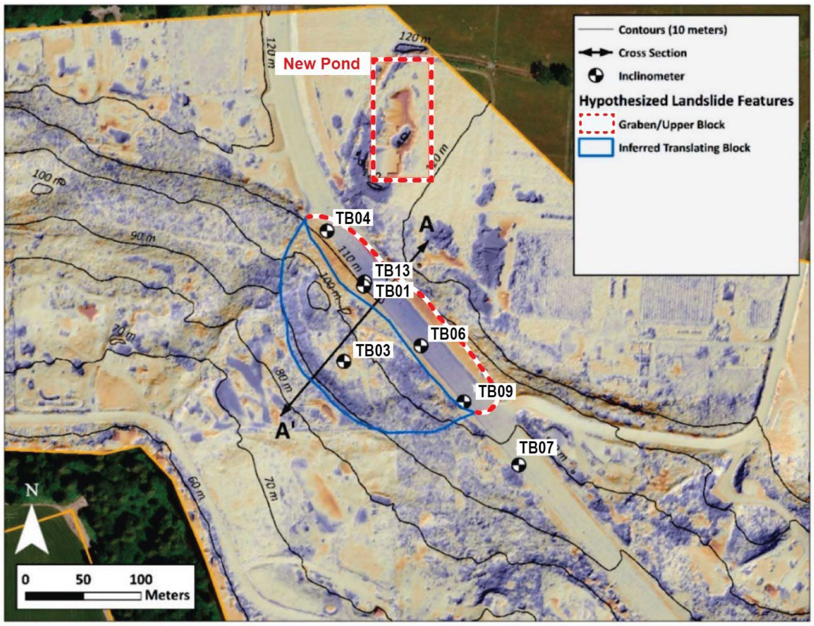


Figure 4. Change analysis of the UAS LiDAR DEM for the Spangler Landslide. Image source: Babbel et al., 2019

TAKEAWAYS

Key takeaways from this example include:

- UAS LiDAR is an efficient and cost-effective technique to map a landslide complex at high resolution and with good accuracy.
- Observations correlated well with findings from inclinometers.
- In topographic scenes with minimal planar objects, software calibrations for determining the lever arm offsets and strip adjustments can be erratic if the software was designed to detect structures and planar objects.

- Some ground filters are biased to the lowest points on a surface rather than smoothing between the low points. This can introduce a slight bias (about 5 centimeters) even on hard surfaces given the noise levels of the system.

COASTAL EROSION AND LANDSLIDING

This section explores the Hooskanaden landslide on the Oregon Coast. Researchers from OSU are monitoring this site to evaluate long-term climate impacts on coastal erosion and landslide activity. UAS can be an important tool in coastal erosion and landslide evaluation surveys to quantify erosional patterns, quantify and show distribution of landslide movements, relate erosional patterns with landslide movement, and characterize the landslide and determine its extents.

HOOSKANADEN

The Hooskanaden slide is in Oregon along the coast near the California border. The main slide is nearly half of a mile long and over 1,800 feet wide and frequently results in damage to Highway 101. Large movements require frequent maintenance and repaving of this section several times a year.

The steep terrain, vegetation, and windy conditions present challenges for the UAS data acquisition. However, ALS surveys are too infrequent to capture movements, and TLS surveys are difficult to safely complete because of the terrain.

Despite these challenges, several UAS surveys have been completed at this site to date. Flights were planned with flightlines oriented north-south to follow the contours of the landslide. Terrain follower software was also implemented to improve the safety of the field operation and quality of the results given the variability of elevation across the slide and the ruggedness of the terrain. For terrain follower, the user inputs a DEM so that the UAS can use that information and follow at a constant height above that DEM.

Another challenge of using UAS is when the slide is actively moving during the survey. GCPs can not be used as the main georeferencing framework option given that the terrain is shifting. For this application, RTK GNSS UAS is critical to minimize the survey time required. After a major failure in February 2019, several UAS flights were conducted (approximately 20 minutes each) to capture detailed orthophotographs as the slide was actively moving (approximately 1-2 feet per hour) for several days after the main rupture. To aid with the georeferencing, five GCPs were placed outside the active area of movement and surveyed before and after each flight.

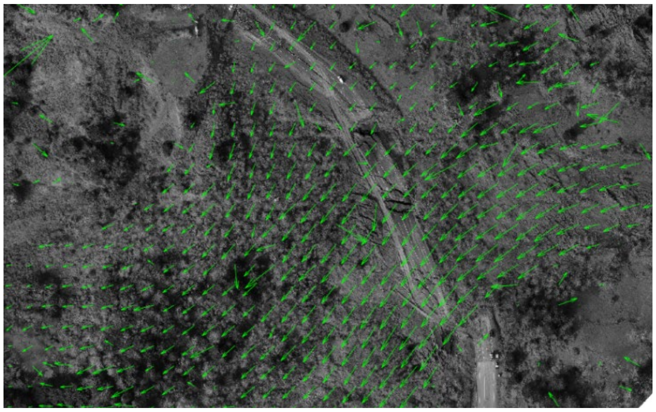


Figure 5. Digital Image Correlation Analysis conducted on the Hooskanaden slide from two flights approximately 18 hours apart while the slide underwent active movement (~1-2 ft per hour). Image Source: OSU

Digital image correlation analyses were conducted on the orthophotos obtained from the RTK GNSS UAS flights (Figure 5). These analyses were helpful to show the patterns of movement across the slide. For example, the pattern of movement rotated for the northern section compared with the southern section that tended to continue to flow southwest. To the west (left) in Figure 6, a zone of compression occurs as the vectors get shorter at the toe of the slide. But while several epochs of data were acquired, some data were lost due to technical glitches in the UAS where images were not stored on the memory card.

The orthoimage was important to detect and identify features across the landslide. Figure 6 (left) shows the damaged road section and status of the temporary access road built to quickly reopen the highway. Figure 6 (right) shows an example of tension cracks that are present across large areas of the slide.

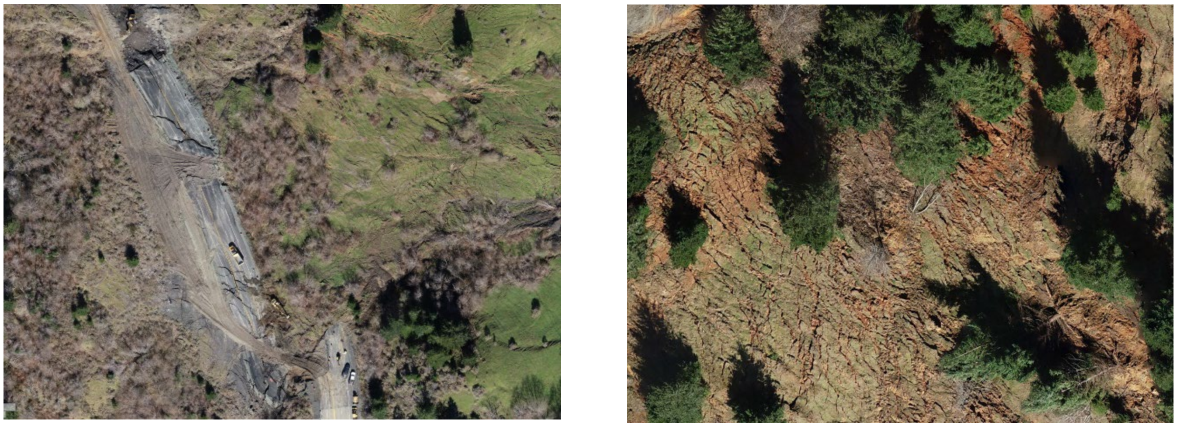
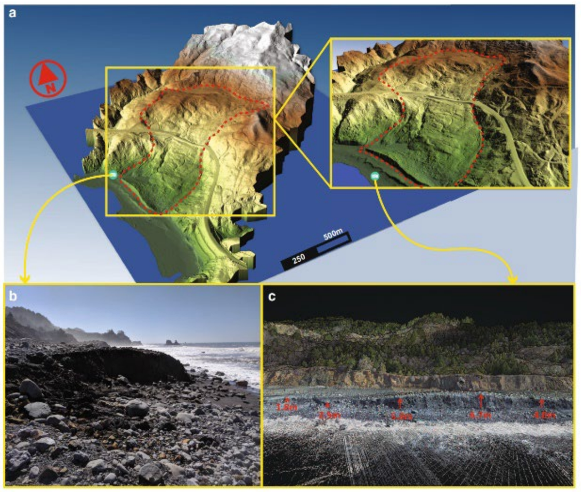


Figure 6. Example orthophotos obtained at the slide showing the damaged roadway (left) and tension cracks (right). Image Source: OSU



Given the extra time required, the UAS LiDAR survey could not be completed until the slide slowed back down so that data would be consistent between flights. However, the detailed DEMs generated from the UAS LiDAR (Figure 7) provided more rigorous quantitative information on the final condition of the slide, particularly in the areas of dense vegetation where bare earth could not be accurately modeled with SfM/MVS photogrammetry.

Figure 7.5 A. 3D view of the UAS data obtained March 15, 2019. Image source: Babbel, 2019. B. Photograph showing uplifted beach cobbles and boulders forming a secondary bluff. Image source: OSU. C. Vertical displacements extracted from the UAS. Image source: Alberti et al., 2020

CONCLUSIONS

UAS may improve safety, efficiency, and data resolution for earth movement applications while still meeting accuracy requirements in most situations. Specific highlights include:

- Both UAS LiDAR and photogrammetric methods can be powerful techniques for landslide and rockfall characterization and assessment.
- UAS technology can provide more viewpoint flexibility than other remote-sensing techniques.
- Ground control can be difficult to set on harsh landslide terrain, especially on rock slopes or if the landslide is actively moving. Using an RTK GNSS drone system with minimal GCPs can be effective in these situations where speed is important.
- Typical photogrammetric GCPs are not reliably captured in UAS LiDAR, which tends to rely on the direct georeferencing solution that is generally more rigorous than SfM/MVS operations.

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