UAV-BASED RECONNAISSANCE AND ANALYSIS OF A LARGE SEISMIC-INDUCED LANDSLIDE IN CENTRAL ITALY

K.W. Franke¹, R.E. Kayen², A. Santo³, F. Chiabrando⁴, J. Blonquist⁵, and B. Barrett⁵

ABSTRACT

Three large earthquakes (Mw 6.0, 5.9, and 6.5) impacted regions of Central Italy August 24, October 26, and October 30 in 2016. Following the Mw6.5 event on October 30, a large wedge-type landslide occurred above the Nera River, approximately 1 kilometer west of Visso. The landslide initiated above the highway Strade Provinciale 209, producing a significant amount of talus that dammed the river and flooded the highway. Because of the challenging site conditions, traditional forms of remote sensing including terrestrial laser scanning were not feasible to perform. This paper presents an innovative solution that was applied for documenting and modeling this landslide. The solution involved the use of an unmanned aerial vehicle (UAV) mounted with a small video camera, and structure from motion (SfM) computer vision image processing for three dimensional point cloud and digital terrain model development. The equipment, methods, and workflow applied in the reconnaissance and modeling of the landslide are described. Results of geostructural and failure mechanism analyses performed on the UAV-based point cloud model are presented. The study ultimately demonstrates the potential usefulness and robustness of UAV-based remote sensing methods.

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Introduction

Between August 24th and October 30th in 2016, an earthquake sequence comprised of 17 events with moment magnitude (Mw) greater than 4.2 was recorded in the Apennine Mountain range of Italy near the villages of Amatrice, Accumoli, Norcia, and Visso by the Rete Sismica Nazionale, which is the national seismic network of Italy, owned and operated by the Instituto Nazionale di Geofisica e Vulcanologia, INGV. Of these 17 events, three main shocks caused the majority of physical damage observed from this earthquake sequence: a Mw = 6.1 event on August 24th, a Mw = 5.9 event on October 26th, and a Mw = 6.5 event on October 30th. Fig. 1 presents a map showing the epicentral locations, moment tensors, and associated faults of these and other significant historical earthquakes that have occurred in this region of Italy, including the 2009 Mw = 6.3 earthquake near L’Aquila.

Because of the mountainous terrain and local geology, landslides occurred in abundance following the three main shocks in 2016. The Geotechnical Extreme Events Reconnaissance (GEER) Association mobilized a team of U.S. geotechnical researchers in collaboration with many Italian geotechnical researchers (organized under the direction of the Italian Geotechnical Society) to observe and document these landslides, as well as other significant geotechnical effects from the earthquake sequence [1]. We, the authors, were members of this team. Due to the difficult terrain and large area that required investigation, we utilized unmanned aerial vehicles (UAVs) to image and later model many of the observed landslides. This paper describes one such landslide, the process used to image and model it using a UAV, and a geostructural analysis performed on the landslide to assess its stability and better understand its failure mechanisms.
Geologic Setting

The central-Italian Apennine chain formed during the Oligocene as Mesozoic and Cenozoic marine carbonate sequences [2] compressed in an east dipping thrust-and-fold system. Since the Pliocene, the interior of the central Apennines has been affected by tectonic extension related to Tyrrhenian subduction and opening of a back-arc basin [3]. The extensional tectonics form series of NW-SE trending, i.e. chain-parallel, normal fault systems, that displace the prior-formed compressive structures and this extension has migrated east-northeastwards [4].

Evidence of ongoing extension of the central Apennine chain is provided by (1) seismicity along SE striking, SW dipping extensional faults, (2) DGPS-geodetic time-series occupations that indicate 3 mm/year NE-SW trending extension [5-6], and (3) borehole, geologic, and
paleoseismological investigations of active normal faults.

The ruptures from the Amatrice and Norcia events occurred principally on the Mt. Vettore normal fault (Fig. 2), a clearly defined group of fault scarps that parallel one-another and likely merge on a listric surface beneath the flanks of the southwest slopes of the Sibillini Mts. Among a suite of parallel faults, the most impressive fault scarp is the “Cordone del Vettore” located at about 2,000 meters above sea level (a.s.l.) in the uppermost portion of the slope [7-11]. Along the bedrock scarp, the exposed fault plane displaces the carbonate rocks, which are overlain by a thin and discontinuous cover of debris on the hanging wall. Rupture was also observed at the base of Mt. Sillibini in the sediment of the Castelluccio Plain intermontane basin.

A less prominent bedrock fault scarp occurs at lower elevation along the same slope of Mt. Vettore (highlighted with white arrows in Figs. 2A and 2B). The fault plane places the carbonate bedrock into contact with slope deposits of Late Pleistocene-Holocene age [8].

![Figure 2. (A & B) Mt. Vettore fault: bedrock fault scarps along the SW slope; the uppermost scarp is the "Cordone del Vettore"; the white arrows indicate the bedrock scarp located in the middle sector of the slope; (C) bedrock fault scarp along the western slope of Palazzo Borghese, between Mt. Porche and Mt. Argentella, NW of Mt. Vettore. Monti Gemelli-Montagna dei Fiori fault, MGMFF.](image)

The Nera Landslide

Following the October 30th event, a large wedge-type landslide occurred approximately 300 meters above the Nera River approximately 1 kilometer west of the town of Visso (42.9290 N 13.0680 E; see Fig. 1) [1]. The event was described to us by one eye witness who was driving his vehicle through the canyon on Strade Provinciale 209 (SP 209), which is adjacent to the Nera River. The
witness, who was traveling to the east towards Visso, had just existed the tunnel located immediately to the west of the landslide site when he saw the falling slide debris and dust cloud in his rearview mirror. Fortunately, the debris had just missed his vehicle. Due to the talus that accumulated below the landslide, the Nera River was immediately dammed and flooded the SP 209.

GEER team estimates of peak ground accelerations (PGAs) at the landslide based on ground motion analysis [1] are 0.40 g during the $M_w = 5.9$ earthquake on October 26$^{th}$, and 0.37g during the $M_w = 6.5$ earthquake on October 30$^{th}$. Interestingly, the ground motion at the site is predicted to be just as large or larger during the October 26$^{th}$ event as it is during the October 30$^{th}$ event due to the site’s closer proximity to the smaller earthquake. It is likely that the October 26$^{th}$ earthquake weakened the already fractured rock prior to the October 30$^{th}$ earthquake.

Fig. 3 presents both an aerial photograph of the Nera Landslide, as well as a three-dimensional (3D) digital terrain model (DTM) of the landslide and surrounding valley. Several environmental factors made the remote sensing of the landslide site difficult. First, the landslide occurred in a relatively narrow river canyon. Second, the landslide occurred in a portion of the canyon that was winding, thus limiting our field of view of the landslide. Third, the flooded highway and risk for continued falling debris limited our access to the landslide and further limiting our field of view. Finally, the landslide occurred approximately 300 meters above the highway on a steep canyon wall. As such, there were portions of the landslide scarp that were simply not visible from the ground. We attempted to use terrestrial laser scanning (TLS) to collect high-resolution and high-accuracy data from the landslide site, but the amount of useful data that was collected was limited due to the environmental factors listed above. A different approach was required to image and model the landslide. We elected to use an unmanned aerial vehicle (UAV) to image the landslide.

![Figure 3](image.jpg)

Figure 3. (A) Aerial photograph of the Nera Landslide captured with a UAV; (B) 3D DTM of the Nera Landslide developed from over 500 digital images of the landslides captured from the UAV.
UAV Data Collection

We incorporated multiple UAV platforms in the Central Italy post-earthquake reconnaissance missions of 2016 [1], but only the platform used to investigate the Nera Landslide will be described in this paper. For the flights and imaging at the landslide, we used two separate DJI™ Phantom 4 Professional platforms, as shown in Fig. 4. This small quadrotor platform is equipped with a built-in 4K video camera with a 1/2.3” CMOS sensor, 94-degree field of view, 12.4 MP image resolution capability, and focal length of infinity.

At the Nera Landslide site, two separate Phantom 4 flights were performed. The first utilized an automated flight path algorithm the collects nadir images at a specified image overlap percentage using the mobile app DroneDeploy (DroneDeploy, San Francisco, CA). Nadir images were collected from an altitude of approximately 700 meters above the SP 206 highway. The second flight was performed manually with better daylight and closer, oblique images of the entire landslide scarp and talus cone. The second flight utilized both 4K video and still images. Still frames were later extracted from the 4K video. In total, over 700 usable images of the landslide were collected from the two UAV 15-minute flights.

![Figure 4. DJI Phantom 4 UAV that was used to image the Nera Landslide during the GEER reconnaissance in 2016.](Image)

Structure from Motion Image Processing

One of the most common forms of UAV-based remote sensing involves the computer (i.e., machine) vision technique called Structure from Motion (SfM) [12-13]. For the GEER reconnaissance, a commercial SfM software program ContextCapture (Bentley Systems, Inc., Exton, PA). The traditional workflow of this and most other commercial and open source SfM platforms includes:

- **Tie Point Extraction** – This step usually incorporates the SIFT (Scale Invariant Feature Transform) algorithm [14] or one of its variants to extract from each image a large number of homologous points (i.e., the sparse point cloud).
- **Camera Orientation and Calibration** – Using camera internal parameters (e.g., focal length, principal point, and distortions), the sparse point cloud is orientated in a local coordinate system (usually connected to the starting reference image) with a relative scale and asset.
• **Bundle Block Adjustment** – Following incorporation of the points, an adjustment is performed to the sparse point cloud to minimize location error. This is usually performed with the Levenberg-Marquardt (LM) method, which is an iterative technique that locates a local minimum of a multivariate function expressed as the sum of squares of several non-linear, real-valued functions.

• **Dense Point Cloud Generation** – Once the sparse point cloud has been developed, dense point cloud generation is initiated using the sparse point cloud as a “lattice” for the dense cloud. The techniques and algorithms used to develop the dense point cloud vary. However, most of these techniques and algorithms incorporate some variant of the Semi Global Matching approach proposed by [15-16].

• **Output Development** – The final 3D dense point cloud enables the development of products such as a DTM digital elevation model (DEM), Orthophoto, and 3D mesh textured model.

For the landslide sites that were imaged with UAVs in Central Italy (including the Nera Landslide), all 3D mesh textured models can be viewed and explored online with a basic Internet browser using the free Acute3D Web Viewer by Bentley Systems, Inc., which allows for basic retrieval of latitude, longitude, and elevation information from the model, as well as basic linear measurement between two points. Links to the available Central Italy 3D landslide models are at [http://prismweb.groups.et.byu.net/gallery2/2016%20Central%20Italy%20Earthquakes/](http://prismweb.groups.et.byu.net/gallery2/2016%20Central%20Italy%20Earthquakes/).

**Geostructural Setting and Analysis of the Failure Mechanism**

Given the difficult accessibility of the head scarp of the Nera Landslide, its geostructural characterization was performed by the interpretation of the results derived by a UAV survey [1]. Following a procedure similar to that described by Santo et al. [17], the 3D point cloud was analyzed with the open source software *Cloud Compare*, and the geostructural analysis was performed with *Dips* (Rocscience, Toronto, ON, Canada). To focus on the validation of the failure mechanism identified in field, the head scarp of the Nera Landslide was isolated in the 3D point cloud model developed with SfM computer vision. The 3D point data provides a more complete data set than that typically obtained from traditional geostructural surveys because point clouds allow better visualization of the studied morphologies and characterization of their geometry through the extraction of linear and angular data. Furthermore, the 3D point cloud provides the coordinates of surveyed points in 3D space, which can be adopted to measure the orientation of discontinuity planes (i.e., facets) bounding the rock mass. The computed dip directions and dip angle of the 3D facets for the Nera Landslide were then used for the definition of five main clusters of facet orientation. The identified joint sets are: Bedding) 45/120; K1) 70/335; K2) 50/270; K3) 70/125 and K4) 70/180. The defined discontinuity sets were selected and classified to obtain a 3D geostructural model, shown in Fig. 5.

As a large number of point coordinates belonging to the landslide facets were detected through this approach, a better description of the geostructural layout of the whole event was performed. It was thus possible to detect that discontinuities of the joint set 45/120 belong to bedding planes slowly dipping southeastwards. The joint system K1 mainly constitutes the slope itself, whereas joint system K2 constitutes the main joint sets affecting the overall instability. In fact, the Nera rock avalanche triggered following a wedge-sliding mechanism that can be seen in Fig. 6.
Figure 5. Perspectives of the 3D geostructural model highlighting the discontinuity sets with different colors. a) Point cloud of the head scarp; b) K1; c) K2; d) K3; e) K4; f) stereo plot of the main joint sets.
Figure 6. Perspectives of the 3D geostructural model highlighting the discontinuity sets with different colors. a) Point cloud of the head scarp; b) K1; c) K2; d) K3; e) K4; f) stereo plot of the main joint sets.

In total, a measured volume of approximately 70,000 m³ of talus was measured in the cone at the bottom of the landslide from the 3D point cloud model. Analysis of the 3D point cloud also produced estimates of the failed rock mass volume between 11,500 m³ and 20,000 m³. While this rock mass would certainly increase in volume upon shattering due to the increased void ratio in the material, such an increase should not exceed 30%. Therefore, the discrepancy in talus can only be explained through the occurrence of additional landslides at that same site prior to the October 30th earthquake. Interestingly, the UAV images and resulting 3D point cloud and meshed surface model captured details of what appears to be a very similar looking head scarp that has aged and darkened considerably. This aged head scarp appears above and slightly to the right of new head scarp, and is shown in Fig. 7. Additional study is needed to analyze this older landslide in order to estimate the timing of its occurrence and the volume of talus that it produced. However, evaluation of that older landslide is beyond the scope of this present study.

Conclusions

This paper summarizes the UAV imaging, SfM computer vision modeling, and geostructural analysis of the Nera Landslide near Visso, Italy following the $M_w = 6.5$ earthquake on October 30th, 2016. Due to difficulty in accessing and visualizing the site, traditional methods of remote sensing the site (including TLS) proved difficult. However, the use of a UAV allowed a clear picture of the landslide to emerge. Using 3D products developed from the SfM analysis of the UAV-based images, geostructural analysis identified the bedding and discontinuity planes the resulted in the occurrence of the landslide. Such an approach could potentially be used in a priori analysis to identify locations of elevated landslide hazard, particularly in areas of similar difficult accessibility.
Figure 7. 3D DTM image of the new head scarp (left) and an older head scarp (right and above) at the Nera Landslide site.

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