Rapid reconnaissance and field observations are essential in advancing earthquake engineering, as data can perish within a few days of the event due to recovery efforts, weather changes, or subsequent failures. Perishable geo-data include slope deformations, response of nonstructural elements, and liquefaction indications such as sand boils. Information collected and documented from immediate reconnaissance efforts in a coordinated, organized, unbiased, and accessible manner is essential in earthquake resilience and mitigation. The collected data form case histories that can be used to advance empirical methodologies and design guidelines. This paper will present an application of using advanced virtual technologies after the major 2016 Mw 7.8 Muisne, Ecuador earthquake. A 3D point cloud was generated using digital and drone images that helped to visualize and understand large-scale failures, well-documented by the GEER (Geotechnical Extreme Events Reconnaissance) team that was on site shortly after the earthquake in collaboration with the Applied Technology Council (ATC). A macro-landslide triggered by the seismic shaking following rainfalls and a pre-shock - all of which contributed to the failure - was replicated in an interactive 3D space model. A Google Earth survey prior to the earthquake was combined with hundreds of drone photographs, to derive sections with automated slope and earth mass volume calculations which would be otherwise cumbersome without this technology. The information shed insight to the observations and was used for analyses using actual ground motion recordings near the landslides.
Drone and Imaging Virtual Tools for Earthquake Reconnaissance: 2016 Muisne, Ecuador Earthquake

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ABSTRACT

Rapid reconnaissance and field observations are essential in advancing earthquake engineering, as data can perish within a few days of the event due to recovery efforts, weather changes, or subsequent failures. Perishable geo-data include slope deformations, response of nonstructural elements, and liquefaction indications such as sand boils. Documented information in a coordinated, organized, unbiased, and accessible manner is essential in advancing empirical methodologies and design guidelines. This paper will demonstrate how advanced virtual 3D technologies can help to understand and analyze large-scale geo-failures using data from the 2016 \( M_s 7.8 \) Muisne, Ecuador earthquake. An interactive 3D space model was generated using digital and drone images by the GEER (Geotechnical Extreme Events Reconnaissance) team in collaboration with the Applied Technology Council (ATC) to replicate a macro-landslide. A survey prior to the earthquake was combined with hundreds of drone photographs, to automatically derive slope sections and corresponding earth volumes. Use of these advanced virtual and design technologies shed light to complicated sequential failures and proved to be an invaluable tool for calculations used for further analysis using actual ground motions, something that would be otherwise less accurate and time consuming.

Introduction

Rapid reconnaissance and field observations are essential in geotechnical earthquake engineering, as it is difficult to replicate in-situ subsurface conditions in the laboratory, but also because data can perish within a few days of the event due to recovery efforts, weather changes, or subsequent failures. Such perishable data include measurements of slope deformations that can evolve over time, response of nonstructural elements that could indicate the intensity and

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directivity of shaking, and sand boils due to liquefaction. Information collected and documented from immediate reconnaissance efforts in a coordinated, organized, unbiased, and easily accessible manner is an essential element that can enhance resiliency and mitigate risks from extreme multi hazards. Collected data can be used to advance empirical methodologies that rely on case histories and particularly from observations of design and construction failures, but also success stories. Lessons learned can enhance geotechnical engineering knowledge and research and lead to modifications to practical methods and design guidelines.

This paper presents an application of advanced virtual technologies for rapid reconnaissance after a major earthquake, including use of drone images to create a 3D point cloud and extract information for visualizing and understanding large-scale failures. The event is the 2016 M\(_{w}\)7.8 Muisne, Ecuador earthquake, for which the authors replicated, in an interactive 3-D space model, a macro-landslide triggered by the shaking that followed significant rainfalls and a pre-shock, all of which contributed to the failure through increment in water pressure, reduction in soil resistance, and/or liquefaction. The event was well-documented by the Geotechnical Extreme Events Reconnaissance (GEER) Association that deployed a team in collaboration with the Applied Technology Council (ATC) shortly after the earthquake. To evaluate the volume of earth mass that moved and the patterns of failure, a Google Earth survey prior to the event was combined with hundreds of photographs taken with drones after the landslides, available from the GEER datasets, to derive various sections with automated slope and volume calculations which would otherwise be cumbersome without this 3D technology.

**2016 M\(_{w}\)7.8 Muisne, Ecuador Earthquake**

**The Main Event**

The April 16\(^{th}\) 2016, Muisne earthquake had moment magnitude M\(_{w}\)7.8 and struck the northwestern region of Ecuador leaving extensive damage throughout the Ecuadorian coast. The earthquake was named after the city nearest to its epicenter (shown on Fig.1), located about 29 km south-southeast of the town of Muisne, in the province of Manabí, at a hypocentral depth of 21 km. In the first 24 hours, over 135 aftershocks were recorded with hundreds more in the weeks that followed. Overall, this earthquake and its aftershocks led to hundreds of fatalities, thousands of injuries, tens of thousands homeless and an economic impact estimated at 3% of the nation’s Gross Domestic Product (GDP) [1]. The event was caused by shallow thrust faulting near the plate boundary where the Nazca subducts beneath the South America plate.

The event drew the attention of the Geotechnical Extreme Events Reconnaissance (GEER) Association that activated a reconnaissance team with funding by the National Science Foundation (NSF) that was joined by structural engineers funded by the Applied Technology Council (ATC). The mission produced a report available at [www.geerassociation.org](http://www.geerassociation.org).

**Recordings**

Strong ground motion acceleration records [2] were provided by the Instituto Geofísico at the Escuela Politécnica Nacional (IG-EPN) which manages the National Accelerometer Network RENAC (Red Nacional de Acelerógrafos) throughout Ecuador. The records were processed
following the PEER standard procedure [2], which includes inspection of record quality, selection of time windows, such as P-waves, S-waves, and coda waves, and component specific filter corner frequencies to optimize the usable frequency range. Details for the 10 selected stations shown on the map of Fig. 1 can be found in [2] and [3]. The Peak Ground Acceleration (PGA) reached a recorded value of 1.41 g at the APED Pedernales station with $V_{s30}$ of 342 m/s.

Figure 1. EW acceleration time histories on a map of Ecuador with recording stations that are color-coded by the intensity of the geo-mean PGA. For details, see [2]

Reconnaissance Methods: Drones and 3D Imaging

Rapid geotechnical reconnaissance used a range of tools and technologies, from conventional to emerging (Fig. 2), including:

- Manual measurements
- Geo-tagged digital photos and videos
- Aeroscanning with military helicopters and cameras
- Global Positioning and Geographic Information Systems (GPS, GIS)
- In-situ field testing, including used of surface wave methods
- Drones
- 3D virtual technologies

The two latter methods were combined, using the high-resolution geotagged videos and images of the drones to recreate, understand, and analyze large-scale observations with 3D modeling and NADIR imaging. Two types of drones were used, shown on Fig. 3: Phantom 4 [4] and Inspire 1 Pro [5]. 3D maps of the heavily damaged IEES Hospital in Manta and a church in Montecristi are shown on Figs. 4 and 5, developed by GEER team member L. Rodriguez using the Pix4D mapping processing software [6]. Orthographic maps of Portoviejo and Manta are shown in Figs. 4 and 5, respectively.
Figure 2. GEER-ATC Ecuador team performing reconnaissance on ground, water and air [2].

Figure 3. Reconnaissance drones: Phantom 4 (left); Inspire 1 Pro (right) [2].

Figure 4. City of Portoviejo: 3D mapping using Pix4D processing software [2].
Application: Landslides at Loor Site in San Isidro, Manabi

The Loor site experienced earthquake-induced landslides. The macro-failure was a succession of three landslides, as shown on Fig. 6. Several factors, other than the seismic shaking itself, contributed to the macro-failure including significant rainfalls in the previous days and a \( M_w 5.7 \) pre-shock that happened 11 minutes before the main shock approximately at the same epicenter. These factors increased the water pressure and reduced the soil resistance with possible triggering of liquefaction, all of which contributed negatively to this failure. A total estimated area of 29 ha (290,000 m\(^2\)) moved both laterally and vertically as shown on Fig. 7.
The main event triggered a first landslide that affected the inferior zone and possible middle of the slope. It seemed to be translational - evident due to lateral movement of soils, with standing trees - at the top and rotational with earth lifting at the base of the slope with rotated and fallen trees. This landslide left the upper portion without support, leading possibly to a second translational landslide almost instantly. A third, rotational, landslide took place causing deformations of the road, cracks around the house, and bulging near the head of the slope. While visual inspection and photo documentation were essential to characterize the slope failure, the information wasn’t enough to quantify the damage and to provide retrofit measurements.

Use of technology, such as Terrestrial Laser Scanning (TLS-LiDAR), Synthetic Aperture Radar (SAR) Interferometry or Unmanned Aerial Vehicles (UAV), also known as drones, comes beneficial for these purposes. Unlike drones, TLS-LiDAR and SAR involve high costs, long hours of work in the field or are not be available for the general public. The following subsections will cover the steps for a simplified methodology to create a 3D point cloud (3DPC) using digital and drone images that helped to visualize and understand the Loor Site failure.
Step #:1 Before Event Data

The very first step is to obtain 3D surface or contours. Historic local municipality maps can be accessed to establish existing conditions prior to the event. In this example, the authors used Google Earth [8] and extracted the 3D Surface (TINS) of the area. Fig. 8 is a snapshot before the earthquake. The more accurate the existing surface is, the more accurate the results will be.

![Figure 8. Step 1: 3D images before failure [8].](image)

Step #:2 On-site Drone Photography Documentation

While it is tempting to shoot videos with flying drone, it is recommended to shoot photos in time lapse mode instead. The photos should have at least fly the drone over the building or site, 50% overlap over the entire area to be captured, to make sure the data collected is useful for the creation of a dense 3DPC. An example of sequence of images are shown On Fig. 9. On average, a picture every 2 to 3 sec provides information for a satisfactory 3DPC. If a denser 3DPC is desired, the time between photos should be reduced, guarantying more overlap between photos and probably extending the time for the drone flight and for postprocessing significantly. One of the advantages of using drones is counting with a sense enough 3DPC for estimation of damage with relatively short time in the field and office collecting data and post-processing information.

![Figure 9. Sequence of drone images with at least 50% overlap [2].](image)
Step #:3 Creation of After Event Model

After collecting a sequence of photos of the area of interest, the photos are to be imported in a computer. The photos will then have to be processed using personal or commercially available software (i.e. AutoDesk Remake [9]) that overlaps images between each other to create a 3D surface, model or PC, and then to overlay it to the image from Step#:1 as illustrated in Fig. 10.

![Image](image_url)

Figure 10. Post-processing of data scheme for construction of 3D products [2].

Step #:4 Overlay of Before and After Models

After the creation of a 3DPC or equivalent 3D model, the user has the option of overlaying the product of Steps #:1 and #:3 for visual comparison and preliminary analysis of the damage. The user has to identify at least 4 points to overlay between the before and after models, ensuring that the comparison performed has more certainty. During this step, the user may navigate through the model and note the sections of major interest for future analysis. Fig. 11 shows a snapshot of the comparison of the before (lighter model) and after (darker model beneath). The figure shows a notable difference in height, which is consistent with the field observations.

![Image](image_url)

Figure 11. Comparison of before and after event models [2].
Step #:5 Analysis of 3DPC

Once the critical sections are defined from Step #:4, the user should proceed to extract them for 2D analyses. The user could extract as many sections as desired, based in the kind of conclusions needed. Having before and after event 3D surfaces can further extend the analysis by computing points and/or volume displaced. Fig. 12 illustrates the 3D surface and the location sections selected, and Fig. 13 and 14 show these sections.

Figure 12. 3D Surface with sections selected for analyses [2].

Figure 13. Section 1 (along hill slope after event). Pre-earthquake slope shown as dashed line [2].
Conclusions

The devastating 2016 Mw 7.8 Muisne, Ecuador earthquake was a reminder that while we cannot predict earthquakes, we can anticipate its potential consequences and use mitigation and protective technology and analytical tools combined with short- and long-term risk goals to anticipate, respond and recover better when it happens. The use of technology for reconnaissance and recovery applications plays a key role in how fast and precise our response is. Combination of technology in response efforts allows decision makers to have a clearer picture of the damage and their implications.

This paper demonstrates how the use of UAV/drones provides useful data to confirm site observations and perform analyses to quantify and visualize damage, which is essential for decision makers that rely on this data to evaluate how to invest in recovery.

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