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Remote sensing for geotechnical earthquake reconnaissance

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ABSTRACT

This paper describes recent efforts that incorporate remote sensing techniques and platforms into geotechnical earthquake reconnaissance to document damage patterns, collect three-dimensional geometries of failures, and measure ground movements. The most-commonly used remote sensing techniques in geotechnical engineering (satellite imagery and LIDAR), as well as unmanned aerial vehicles (UAV), are introduced and recent case histories of the use of these techniques in reconnaissance efforts are provided. These examples demonstrate the potential for remote sensing to improve our understanding of geotechnical effects both at a regional scale and at a local level. The use of remote sensing to measure ground movements is particularly noteworthy and has the potential to provide data sets that will improve our ability to quantitatively predict the consequences of liquefaction and landslides. However, to realize this potential, investments must be made in collecting appropriate pre-earthquake data.

1. Introduction

Advances in geotechnical earthquake engineering have been initiated in large part by observations documented during previous earthquakes. Thus, reconnaissance efforts are critical for evolving our field, and organizations such as the Geotechnical Extreme Events Reconnaissance (GEER) Association have placed significant emphasis on collecting perishable data after earthquakes. Over the last ten years remote sensing has increasingly played a role in geotechnical earthquake reconnaissance through the use of satellite imagery and LIDAR, and more recently the use of unmanned aerial vehicles (UAV). Remote sensing can provide a more holistic view of the geotechnical effects of an earthquake and this view can be integrated with other data within a geospatial framework, allowing for the identification of relationships that could not be recognized otherwise (e.g., [34,36,11]).

There are three general application areas in which remote sensing has been used to document the geotechnical effects of earthquakes: (1) documenting the locations of earthquake damage and damage patterns, (2) developing three-dimensional digital elevation models of failure geometries, and (3) measuring ground movements. When identifying the relevant remote sensing techniques for any of these applications there are always tradeoffs in terms of the spatial resolution/accuracy of the data relative to the aerial coverage [36]. Higher resolution data with higher accuracy typically only cover relatively small areas, such as a single failure site. To capture a larger area, such as an entire city, one must often sacrifice spatial resolution and accuracy. However, depending on the eventual use of the data, the larger aerial context may be more important than the spatial resolution and higher accuracy. Another consideration is the availability of pre-earthquake data that can be used with post-earthquake data to evaluate changes and movements due to the earthquake. The availability of pre-earthquake data, and the cost required to obtain it, influences the types of remote sensing data analysis that can be performed and the information that can be produced.

This paper describes recent and on-going research in which remote sensing has been integrated into the reconnaissance of earthquakes, and other natural hazards, to better understand the geotechnical effects of these events. In particular, the use of satellite imagery, LIDAR, and unmanned aerial vehicles is highlighted within the context of documenting damage patterns, developing digital elevation models, and measuring ground movements. After a synthesis review of activities in these areas, three detailed case histories are presented regarding landslide identification, measurement of liquefaction movements, and measurement of ground movement.

2. Remote sensing techniques and platforms

2.1. Satellite and aerial imagery

Satellite and aerial imagery can provide important information about the geotechnical effects of earthquakes at a regional scale,

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and in some instances at the scale of a single site. A multitude of satellite sensors currently are imaging the earth at different pixel resolutions, at different repeat cycles between acquisitions, and within different spectral bands of the electromagnetic spectrum. The available sensors are continuously changing as new sensors are launched and others are retired. Today, the highest resolution commercial sensor is WorldView-3, launched in August 2014, which provides panchromatic data (450–800 nm wavelengths, typically viewed in grayscale) at 0.30 m resolution. Multispectral data (finer spectral bands about 50–60 nm wide within the visible and near-infrared wavelengths of the electromagnetic spectrum, between 400 and 1000 nm) are available at ~1.25 m resolution and shortwave infrared data (SWIR, 1000–2500 nm wavelengths) at ~4 m resolution (http://www.satimagingcorp.com/satellite-sensors/worldview-3/). The highest spatial resolution is available only for panchromatic data because the wider spectral range is required to collect enough solar radiation for small pixel sizes. For the same reason, the narrower multispectral bands are available at larger pixel sizes, and the SWIR bands are available at even larger pixel sizes because of the reduced solar radiation at these wavelengths. The data within the finer multispectral and SWIR bands provide important information about the different types of landcover (e.g., vegetation, soil, moisture, etc.), which can be important for some applications such as identifying liquefaction ejecta.

Satellite sensors that collect reflected solar radiation from the earth surface are considered passive sensors because they passively collect the availability solar radiation. These passive sensors are negatively impacted by clouds because clouds impede the travel of the solar radiation towards the sensor. An alternative to a passive sensor is an active sensor, such as synthetic aperture radar (SAR), which generates its own energy and operates at longer wavelengths (anywhere from 2 cm to 30 cm depending on the sensor) such that clouds do not significantly influence the travel of the waves. In addition to recording the amplitude of the backscattered radar waves, SAR also records the phase of the waves, which allows SAR image pairs to be processed to measure precise ground movements within the line of sight of the radar. Although sensors like SAR can image at night and through clouds, they often have lower spatial resolution (10–30 m) and require significant data manipulation and processing to provide useful information. Nonetheless, it has become almost commonplace to use SAR to image surface fault rupture movements (e.g., [45]), and others have used the loss of SAR phase coherence as an indicator of liquefaction (e.g., [1]).

In some ways, satellite imagery is a variant of aerial photography, which has been used for decades to document earthquake effects. Aerial photographs commonly are acquired from an aircraft and, similar to satellite imagery, can collect data within different parts of the electromagnetic spectrum. Both aerial photographs and satellite imagery can be taken in stereo such that three-dimensional models can be made of the ground surface. Aerial photographs are typically of higher spatial resolution than satellite imagery due to the closer proximity to the ground surface.

Various techniques are available to document the effects of earthquakes using satellite and aerial imagery. These techniques range from simple visual/manual classification methods to semi-automated thematic classification and change detection techniques. Important issues to consider when selecting the appropriate analysis technique are the availability of pre-event imagery, the size of the area of interest, and the time required for analysis. Generally, visual/manual classification and thematic classification can be applied successfully using post-event imagery alone, while change detection requires pre- and post-event imagery. Nonetheless, visual/manual classification still can benefit from the availability of pre-event imagery.

2.2. LIDAR

LIDAR is an active remote sensing technique that involves the collection of reflected and backscattered light from the active illumination of the ground using a laser source. A laser beam scans across an area, repeatedly shooting out a pulse of light that hits the surface and scatters a portion of the light back to the sensor. By timing the round trip of each laser pulse, the distance is determined for each scan position. Knowing the position and orientation of the laser, a group of (x, y, z) coordinates, referred to as a point cloud, is acquired and the point cloud can be processed to develop a digital elevation model (DEM). The small size and modularity of LIDAR instruments allow these systems to be mounted in small aircraft to collect data over large areas, or on a tripod to collect more detailed data for smaller areas (Fig. 1).

For airborne LIDAR, the location and orientation of the sensor is provided by differential GPS and an inertial measuring unit (IMU). Synchronization of the independent times between the sensor, GPS, and IMU is one of the most challenging aspects of system design. The primary sources of error in airborne LIDAR data result from timing errors with the laser, GPS related errors, misalignment of the IMU, and integration of the data streams [35]. Ground-based terrestrial LIDAR does not suffer from the same issues because often the sensor is located in a single, fixed location during data collection. However, the location of the LIDAR must be tracked when the terrestrial LIDAR system is mounted on a moving vehicle. Ground-based LIDAR cannot see behind objects and thus the first surface encountered casts a shadow over objects behind it, as shown in Fig. 1b. To obtain full coverage, the LIDAR scanner must be moved to other locations surrounding the target area and the multiple scans georeferenced to one another. Through data processing techniques, a digital surface model of the feature can be developed (Fig. 1c) that can be used for analysis (Fig. 1d).

2.3. Unmanned aerial vehicles

Unmanned aerial vehicles (UAVs, also commonly referred to as "drones") are aerial robots that can be remotely controlled by one or more operators (though some can operate with various levels of autonomy) and can carry a wide variety of sensors. While strictly not a remote sensing technique, this technology is becoming more common as a platform for remote sensing. The size and number of sensors that can be carried on a UAV depends upon the size, flight endurance, and payload capacity of the UAV. In particular, exploding interest in the use of small UAVs (i.e., sUAVs), which are often defined as having a combined total platform plus sensor weight of less than 23 kg (~50 lb), is leading many scientists and engineers to explore new UAV applications in their respective fields of study. sUAVs offer the advantage of obtaining data from a low-altitude aerial vantage point at a relatively low cost, thus allowing the scientist and engineer to economically and repetitively obtain a birds-eye view of their site of interest while avoiding many of the obstacles and occlusions that are often encountered with terrestrial remote sensing techniques. Today, the most common sensor deployed on a UAV is a digital camera. Although LIDAR systems can be deployed, they are currently very expensive and are used far less often.

A wide range of sUAV platform types are currently available, and many more are being developed and evaluated as interest in sUAVs continues to grow. One can currently classify most sUAV platforms into three general types: (1) single-rotor platforms, (2) multi-rotor platforms, and (3) fixed-wing platforms. Fig. 2 shows examples of each of these types of sUAV platforms. The collection of data using sUAVs is potentially much cheaper and quicker than collecting similar data using a traditional aircraft. A few researchers have recently documented the use of UAVs for performing post-earthquake reconnaissance and damage assessment. For example, Gong et al. [15]

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