

Earthquake geotechnical engineering reconnaissance methods and advances

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ABSTRACT: Earthquake geotechnical engineering is an experience-driven discipline. Field observations are particularly important, because it is difficult to replicate in the laboratory the characteristics and response of in situ soil deposits. Much of the data generated by a major earthquake is perishable, so it is critical that it is collected soon after an event occurs. Detailed mapping and surveying of damaged and undamaged areas provides the data for the well-documented case histories that drive the development of many of the earthquake geotechnical engineering design procedures. New technologies are being employed to capture earthquake-induced ground deformation, including Light Detection and Ranging, Structure-from-Motion, and Unmanned Aerial Vehicles. Post-earthquake reconnaissance has moved beyond taking photographs and field notes to taking advantage of technologies that can capture ground and structure deformations more completely and accurately. Moreover, electronic data enables effective sharing and archiving of the measurements. Unanticipated observations from major events often catalyze new research directions. Important advancements are possible through post-event research if their effects are captured and shared effectively. An overview of some of recent integrated technology deployments and their role in advancing knowledge are presented.

1 INTRODUCTION

There have been major improvements in scientific understanding and subsequent advances in earthquake engineering practice in the aftermath of significant earthquakes. Events that have significantly influenced earthquake engineering research and practice include the 1964 Niigata, 1985 Mexico City, 1989 Loma Prieta, 1994 Northridge, 1995 Kobe, 1999 Kocaeli, 1999 Chi-Chi, 2010 Chile, 2011 Tohoku, 2010-2011 Canterbury, and 2016 Central Italy earthquakes. Each major earthquake potentially provides critical lessons that can advance knowledge and understanding.

Field case histories are the cornerstone of geotechnical engineering. Much of the data and information generated by an earthquake is perishable and therefore must be collected within a few days or weeks of the event. The removal of debris during recovery operations and restoration of transportation networks and lifelines quickly obscures observable significant damage, and hence, it obscures critical insight that could advance the profession. Earthquake geotechnical engineers should respond effectively so that potentially critical lessons are not missed.

In this paper, examples of recent reconnaissance efforts by the U.S. National Science Foundation (NSF)-sponsored Geotechnical Extreme Events Reconnaissance (GEER) Association are showcased to illustrate the achievements possible when insightful field case histories are well-documented. Although GEER originated in the United States (US) for earthquake reconnaissance, GEER includes members worldwide and expanded in 2011 to include other extreme events such as hurricanes, floods and landslides. GEER works closely with other reconnaissance organizations to capture perishable data following major events so that the profession can learn from them.

2 GEER

Since 1999, GEER has responded to 58 events worldwide with 69% of those being earthquake related. The distribution of responses by event type and timeline distribution of responses for this period is shown in Figure 1. From 1999 to 2011, responses, which were dominated by post-earthquake activities, were comparable for North America and Asia (~30% each) and likewise comparable for South America, Europe, and Australasia (~15% each). In contrast, for the period 2012 to 2017, which reflects the period of the broader GEER event mandate to survey extreme events in addition to earthquakes, the distribution of events for North America (~46%) is comparable to the responses to the rest of the world combined (~54%). While the average annual response rate since 1999 is about three, the response rate in the past four years has been about 7 and is reflective of both the broadening of the GEER mandate and the increasing number of unprecedented extreme events that have occurred. For each GEER response, web-based reports were typically published within less than 2 months of completion of the field reconnaissance activities. These reports are archived on the GEER website (www.geerassociation.org) and are frequently used by researchers, engineers and government agencies.

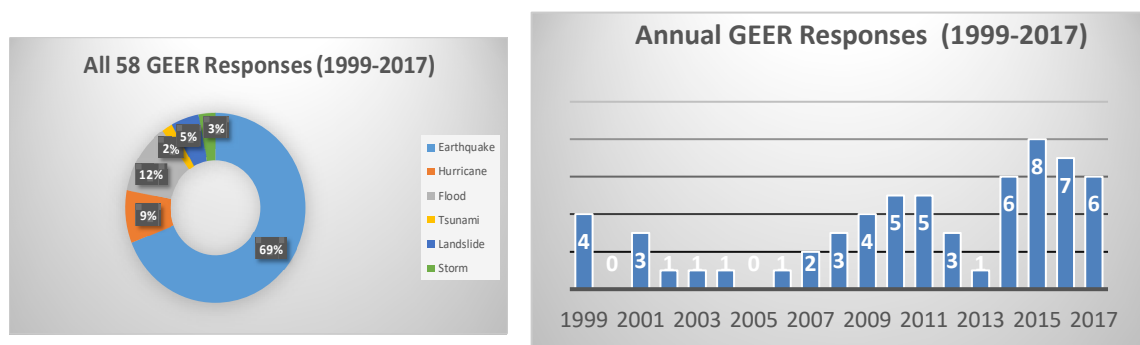


Figure 1. Summary of GEER Event Responses (1999-2017).

GEER reports (each with its citable Digital Object Identifier (DOI)) are the primary contributions of a GEER response. Often additional updated information is presented in journal papers published later. The full details of the observations and data collected during recent GEER responses are described in the comprehensive reports available on the GEER website. In all cases, GEER team members collaborated with various local, state and federal agencies. A common characteristic and lesson of GEER responses is the reinforcement of the need for timely well-coordinated responses that allow for critical perishable data to be gathered. Apart from the inherent value of the data itself, it also provides critical insight into responses that need additional study and investigation, either through physical experimentation or numerical simulations. Further, the beneficial role of emerging advanced technology-based data collection continues to increase.

The following summaries of some recent GEER responses illustrate the outcomes of GEER activities:

- GEER deployed several teams within 24 hours to document the geotechnical effects of the 2014 M_w 6.0 Napa, California earthquake. The California Highway Patrol provided a helicopter to enable a GEER team member and a U.S. Geological Survey employee to perform an aerial survey of the affected region. The reconnaissance documented the effects of strong shaking and ground failure on infrastructure, with a focus on surface fault rupture and differential ground movements. Initial observations showed a remarkable absence of liquefaction or landslide induced ground deformations. However, there was well defined surface rupture that produced various types of damage to structures and there was a pattern of damage to sidewalks and curbs suggesting sympathetic ground deformations within the vicinity of the fault zone. Additionally, important lessons were learned about the impacts of the earthquake on the Napa Valley wine industry. Wineries with underground storage suffered relatively minor damage whereas some above-ground wine storage facilities suffered significant damage.

- A GEER team responded after the 2015 M_w 7.8 Gorkha, Nepal earthquake and its resultant aftershocks, which had a devastating impact on Nepal. The earthquake sequence resulted in nearly 9000 deaths, tens of thousands of injuries, and left hundreds of thousands of inhabitants homeless. With economic losses estimated at several billion US dollars, the financial impact to Nepal was severe and the rebuilding phase will likely span many years. The overall distribution of damage indicated significant ground motion directivity, with pronounced damage to the east and comparatively little damage to the west. Although modern buildings constructed within the basin generally performed well, local occurrences of heavy damage and collapse of reinforced concrete structures were observed. Ground failures in the basin included cyclic failure of silty clay, lateral spreading, and liquefaction.
- GEER teams deployed in a phased manner to the devastating earthquake sequence that struck central Italy from August-October 2016. Innovative reconnaissance approaches combined satellite imagery, local imagery from Light Imaging Detection and Ranging (LIDAR) and Unmanned Aerial Vehicle (UAV)-based photographs, and traditional field mapping was undertaken of structural damage patterns, landslides, surface fault rupture, and other effects. Observations made during the GEER reconnaissance activities are having an impact in research on fragility of masonry structures, ground motions from normal fault earthquakes, landslides in complex geologic terrain, and surface fault rupture.
- GEER collaborated with researchers from the Universidad Nacional Autónoma de México after the 2017 M_w 7.1 Puebla - Mexico City, Mexico earthquake to document the event impacts. Observed foundation performance in areas of structural damage varied considerably. Structural damage was concentrated in areas where the structure's fundamental period aligned with the fundamental period of the soft Mexico City clay deposit. Numerous cases of seismic-induced settlements ranging from 10 to 150 mm were observed in the free-field soils around end-bearing pile-supported structures. Several cases of tilted structures (1 to 3 degrees) were observed. These structures generally were supported on combined friction pile and mat slab foundation systems.

3 POST-EARTHQUAKE RESPONSE

Soon after an extreme event occurs, it is crucial to identify the primary opportunities that the event presents for advancing the profession, while maintaining the flexibility required to adjust a team's focus based on early observations. Accordingly, areas to investigate in greater depth are identified, and *GoogleEarth*TM and *Slack*TM are used to coordinate and record team member activities and their field observations. Aerial surveys and remote sensing are useful for getting an overall perspective of the geotechnical impacts of the event. Aerial photographs taken after an event can be compared to those from existing databases to help define damage patterns that can provide invaluable planning insights. The data and information that can be collected by post-event reconnaissance teams includes high quality digital photographs of damage both from satellite and aircraft as well as from the ground. Reconnaissance activities also include geologic and damage mapping, shear wave velocity profiling using the multi-channel analysis of surface waves (MASW) techniques, and dynamic cone penetration tests (DCPT) at liquefaction sites. All observations are positioned accurately using GPS coordinates, time-stamped, and recorded digitally for effective sharing.

A critical question reconnaissance team members must consider continually is whether the documentation of the effects of an earthquake at a particular site advance the profession? Gaps in knowledge and understanding should focus the reconnaissance efforts. If the observations at a site are expected, then documenting this site is of lower importance. For instance, if a very loose, saturated, young, shallow clean sand deposit liquefies in an open field when shaken intensely, the site data would produce a data point that would not influence future cyclic resistance ratio (CRR) curves in simplified liquefaction triggering procedures. Conversely, if a medium dense, saturated slightly plastic clayey silty sand liquefies under moderate earthquake shaking at a site that affects the performance of a critical natural gas pipeline system, documentation of this site would produce both crucial liquefaction triggering data and field performance data on the effects of liquefaction on critical infrastructure. Importantly, one well-documented highly influential field case

history is more valuable than hundreds of photographs of earthquake damage, much of which would be expected given the level of earthquake shaking and the types of soil deposits involved.

All possible mechanisms should be considered while surveying an important site. All facts should be collected so that all potential hypotheses that might explain the observed seismic performance may be evaluated robustly later. Focusing prematurely on figuring out why the ground or engineered system failed leads one to collect only those facts that support an initially favored hypothesis. A team member should play the role of a devil's advocate to combat a majority opinion of other team members of a favored hypothesis. Remaining objective is critical while team members work to collect all possible information and data. There will always be time later to figure out why something happened if all the pertinent observations and facts are collected during the field reconnaissance stage.

Re-examining both excellent and poor post-earthquake reconnaissance reports before going to the field is useful in reminding one of what are the key elements of a well-documented case history and the shortcomings of a poorly-documented case history that is never relied upon in research or practice. The goal is obviously to collect the data required to prepare a well-documented field case history that can stand the test of time and make an important contribution to advancing knowledge and understanding. If possible, return to a site several times to examine things missed the first time. If this is not possible, devote extra time before departing a site to reviewing the collected data and notes to ensure they are as comprehensive and correct as possible given the resources available.

Documenting good and poor performance is important to advance performance-based earthquake engineering. There is a natural disposition to focus on collected data that documents failures. However, documentation of good performance of the ground and an engineered system when severely tested by an earthquake is equally important. Often the most impactful field case histories are those instances when the ground or structure were moderately damaged. The transitions from negligible or light damage to moderate damage and from moderate damage to severe damage are important to document. For example, documenting a case when a liquefaction-induced lateral spread displaces only a few hundred millimeters can be informative and fill the knowledge gap between lateral spread case histories that displaced a limited amount or a large amount.

4 POST-EARTHQUAKE RECONNAISSANCE METHODS

Conventional techniques for performing effective geotechnical reconnaissance are delineated in the GEER reconnaissance guidance manual (GEER 2014). However, earthquake geotechnical engineers have always understood the need to develop and apply new technologies and techniques that document more quantitatively the effects of earthquakes on infrastructure. GEER is an early adopter of advanced data collection technologies. From the adoption of handheld GPS systems in 1999 in Turkey, to dedicated mobile computing software data collection solutions in 2001 in India, to satellite and terrestrial LIDAR scanning based assessments of landslide distributions in Japan in 2006, to use of *GoogleEarth*TM photo logs in 2007 in Japan, to use of social media data to assess damage in 2013 in Colorado, to use of UAV platforms in 2014 in Chile, GEER teams have led the natural hazards reconnaissance community in adopting and deploying new advanced technologies. Apart from the inherent benefits associated with using these technologies in terms of data quality and quantity, they yield significant efficiencies in team performance and facilitate deployment of GEER resources in locations likely to yield the most impactful perishable data.

LIDAR has been used in GEER responses to document damage to earth structures and ground failure after several extreme events. For example, aerial photography and ground-based LIDAR were used to document the Shiroya landslide, a large landslide produced by the shaking in the 2004 Niigata-ken Chuetsu, Japan earthquake, which adversely impacted a major road and adjacent bridge (Rathje et al. 2006). Another example is the detailed depiction of a failed highway overpass embankment in Chile, which is shown in Figure 2. The LIDAR image is a detailed 3-D digital surface photograph wherein each pixel is identified with its x, y, and z location. Efforts to utilize LIDAR to capture pre-event urban conditions (e.g., Rovithis et al. 2017) will enhance the ability for post-event scans to capture ground movements.



Figure 2. Ground-based LIDAR and optical images of a failed overpass embankment on Ruta 5 from the 2010 Chile Earthquake (LIDAR survey by Kayen presented in Bray and Frost 2010).

Remote sensing, via spaceborne or airborne sensors, are other tools that have emerged as a crucial component of documenting the effects of natural disasters (Rathje and Franke 2016). Commercial optical satellites routinely obtain sub-meter imagery that can be used to assess the geographical distribution of damage. Satellite imagery is georeferenced to standard cartographic projections, and thus observations from the imagery can be fused with ancillary information such as geologic maps, topographic maps, or any other information that has been georeferenced. Satellite imagery was used to document the distribution of landslides from the 2004 Niigata-ken Chuetsu earthquake (Rathje et al. 2006), to investigate the influence of geologic, topographic, and seismologic conditions on urban damage patterns from the 2010 Haiti earthquake (Rathje et al. 2011), and to measure sub-meter lateral spread displacements from the 2011 Christchurch earthquake (Rathje et al. 2017c). Another example is the integrated documentation of geotechnical damage along the primary north-south highway in Chile (Ruta 5) following the 2010 Chile earthquake by Frost and Turel (2011).

UAVs are aerial robots that can be remotely controlled and can carry a wide variety of sensors. This technology is becoming more common as a platform for remote sensing in the aftermath of catastrophic events. The most common sensor deployed on a UAV is a digital camera. Although LIDAR systems can be deployed, they are used less often. The images collected by a UAV can be used to visually examine earthquake effects over a large site from a broader perspective, but they can also be used to develop 3D point clouds of a site. The development of these 3D point clouds requires hundreds to thousands of images and integration of these digital images with stereo photogrammetry/computer vision techniques, such as Structure-from-Motion (SfM; Marr and Nishihara 1978; Snavely et al. 2008).

The emergence of high-resolution high-fidelity data sets has been a catalyst for some of the latest new insights. Unanticipated observations from significant events often define alternative research directions. As an example, the results of studies of soil liquefaction, especially those involving soils with significant fines content, were motivated largely by observations of liquefaction and ground softening documented by NSF-sponsored GEER reconnaissance efforts after earthquakes in Turkey, Taiwan, and New Zealand. The careful documentation of liquefaction following the 1999 Kocaeli earthquake (Bray and Stewart 2000) provided much of the data that advanced the profession's understanding of liquefaction of fine-grained soils and led to important new criteria for evaluating the liquefaction susceptibility of these soils (e.g., Bray and Sancio 2006). Similarly, the documenting of liquefaction following the Canterbury earthquake sequence has yielded new insights into the settlement of structures on liquefied soils and procedures to evaluate them (Bray and Macedo 2017). If the geotechnical engineering profession does not continue to look for new insights following future earthquakes with more extensive data sets, important research opportunities will be lost.

Notwithstanding the important emerging role of new hardware and software technologies as noted above, long-established and widely used traditional methods of data collection and information sources remain a critical component of GEER reconnaissance activities. Detailed mapping

is possible with differential GPS devices, such as total stations. The importance of detailed mapping and surveying of damaged areas relative to general damage surveys cannot be overemphasized, as they provide the data for ground-referencing well-documented case histories that drive the development of many of the empirical design procedures used in earthquake engineering practice. Geologic maps, topographic maps, soil reports, and damage reports can be collected from various sources to help complete the picture of what happened and prepare for subsequent support studies that allow the profession to discern why it happened.

Field observations, detailed mapping and measurements, and remote sensing technologies provide diverse data at different spatial and temporal scales. Together, they offer opportunities to develop more comprehensive observations of damage. Additionally, the fusion of observations from different sources can lead to more comprehensive assessments of failure mechanisms. The data can also be integrated with other types of geospatial information, such as geologic maps, topographic maps, and *Shakemaps* of ground motion, to explore the relationships between damage and potentially important factors. This integration is facilitated by the fact that all damage observations can be geo-referenced to standard cartographic projections using GPS. Data fusion can be facilitated through open-access data repositories and cloud-based data analysis tools that can access various datasets where they reside in the cloud.

5 ILLUSTRATIVE POST-EARTHQUAKE RECONNAISSANCE EFFORTS

As stated previously, the primary deliverable of a GEER response is its reports and datasets collected during the post-earthquake reconnaissance activities. A few expanded summaries are provided below to illustrate several uses of advanced technologies to effectively capture perishable data following an earthquake.

5.1 2016 Meinong, Taiwan Earthquake and Interactive Fly-Through Models

The M_w 6.3 Meinong, Taiwan earthquake struck the southern region of Taiwan on February 6, 2016. Left-lateral strike-slip fault rupture with minor reverse fault movement occurred on a previously unmapped fault and produced strong ground shaking and subsequent structural damage to the Tainan area. The ground shaking was accompanied by landsliding, liquefaction, and lateral spreading, and most liquefaction was confined to spots containing low-quality backfill soil (Sun et al. 2016a). A GEER reconnaissance team deployed rapidly after local emergency response efforts concluded, and they spent one week observing and collecting perishable data. Reconnaissance efforts focused on the geologic influence on ground motions, liquefaction of sandy soils, performance of buildings and foundations atop liquefiable soil, and performance of non-symmetrical and soft-story buildings. The GEER team observed that buildings with continuous, well-connected foundations, or sitting atop basements, performed well in areas where liquefaction occurred, whereas those without well-connected foundations incurred heavy damage (Sun et al. 2016a).

Quantitative imagery was obtained by the GEER team using LIDAR to create 3D, interactive fly-through models that allow viewers to virtually enter and exit structures and quantify damage (Sun et al. 2016b). Aerial imagery via a quadcopter UAV also provided photogrammetry datasets with which to create 3D point cloud models using SfM. The point cloud data did not require control points on the ground; instead, the UAV photos for this reconnaissance were geotagged so that the relative locations of the viewpoints of each image could be used directly to create high-resolution, 3D models such as that shown in Figure 3.

5.2 2016 Central Italy Earthquake Sequence and UAV Variety

The central Italy earthquake sequence began with a M_w 6.1 earthquake occurring on August 24, 2016. This event caused significant damage, mostly to unreinforced masonry homes, in the villages of Arquata del Tronto, Accumoli, Amatrice, and Pescara del Tronto, causing 299 fatalities (Zimmaro and Stewart 2016). Evacuation orders were put in effect before two more large earthquakes of M_w 5.9 and 6.5 occurred on October 26 and 30, 2016, respectively, and caused more damage to the villages of Visso, Ussita, and Norcia (Zimmaro and Stewart 2017). The GEER

reconnaissance team was comprised of U.S. and Italian researchers and practicing engineers who documented the earthquake effects on slopes, villages, and major infrastructure.

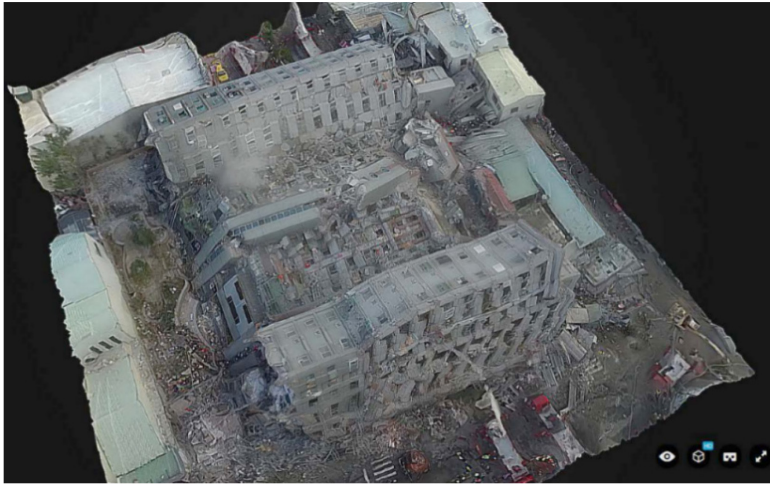


Figure 3. SfM model of the collapsed Weiguan Jinlong Complex developed using UAV photogrammetry (23.0052° N 120.261° E; Sun et al. 2016a).

The reconnaissance team utilized a variety of UAVs equipped with high-resolution cameras to obtain photogrammetric imagery with which to develop 3D models of damage sites using SfM. Three types of UAVs were used to obtain imagery from the Central Italy earthquakes: a fixed-wing UAV, a quadcopter UAV, and a helicopter UAV, the specifications of each of which are available in Zimmaro and Stewart (2016). While the quadcopter and helicopter UAVs needed to be manually controlled, the fixed-wing UAV was programmed to follow a specific flight path using selected waypoints. The automated capabilities of the fixed-wing UAV allowed the GEER team to produce orthophotos of entire towns.

SfM proved to be especially useful in obtaining 3D imagery for significant landslide events occurring in rugged or steep terrain, in heavily vegetated areas, or in other areas with limited site access. For example, Figure 4 shows a 3D image of a slope failure in Pescara del Tronto resulting from retaining wall failure. The SfM imagery and point cloud data can be used to perform further quantitative analyses post-reconnaissance, and this data can be further verified for accuracy by combining them with other geomatics technologies such as LIDAR.



Figure 4. 3D SfM model of a slope failure in Pescara del Tronto possibly caused by a retaining wall collapse (42.75109° N 13.27208° E; SfM by Franke et al. presented in Zimmaro and Stewart 2016).

5.3 2016 Kaikoura, New Zealand Earthquake and Rapid Satellite Image Analysis

The 2016 M_w 7.8 Kaikoura, New Zealand earthquake initiated in the Waiau plains in North Canterbury on November 14 and ruptured dozens of fault segments in and north of Kaikoura. The rupture progressed north-eastward, producing surface fault rupture, strong ground shaking, landslides, liquefaction, and lateral spreading in the South Island of New Zealand and in the capital city of Wellington (Cubrinovski and Bray 2017). Due to the large impacted area from this earthquake, a collaborative effort between teams from GEER, GNS Science, and the University of Canterbury (UC) was undertaken to document the effects of the Kaikoura earthquake. One GNS-UC-GEER team documented the effects of surface fault rupture on the built environment and another GNS-UC-GEER team documented the occurrence of landslides and produced a thorough inventory of landslides. A joint QuakeCoRE-GEER team focused on earthquake ground motions, site effects, geotechnical effects, social impacts, and emergency response in Wellington and South Island (Bradley et al. 2017). Key observations and preliminary findings are presented in papers such as Cubrinovski et al. (2017, 2018).

A unique feature of the response to this earthquake was the development of a detailed landslide inventory within 8 days of the event, and this inventory was used to guide the GNS-UC-GEER reconnaissance efforts. The detailed landslide inventory utilized both moderate resolution (15 m) Landsat 8 imagery and high resolution (1.2 m) WorldView-2 and WorldView-3 imagery. The Landsat 8 imagery covered an area of about 1800 km² and was used initially because it was available within 24 hours of the event. The high-resolution imagery became available starting about 2 days after the event and the final set of 65 images covered a broader area of about 7400 km².

Visual interpretation was used to identify the landslides. This approach relied on the ability to see the landslides in the imagery. The simplest approach was to display the imagery as natural color, the color observed with the naked eye, and landslides were generally identified as locations where the vegetation was stripped away, exposing the underlying soil and rock material. The sharp contrast in color was easily distinguished when the proper color bands were selected and cloud cover was minimal to non-existent. To ensure that an area of stripped vegetation did not represent a landslide existing before the earthquake, pre-event imagery was checked manually (Figure 5). Each landslide was identified as a polygon, and no attempt was made to differentiate the source area from the landslide debris. The total number of landslides in the final inventory was 1331. The digital landslide inventory was brought to the field to guide reconnaissance efforts and was ground-truthed in real-time during helicopter reconnaissance over the affected area. The landslide inventory was initially posted on the GEER website (Rathje et al. 2017b), but ultimately was formally published as a dataset within the *DesignSafe* cyberinfrastructure (Rathje et al. 2017d).

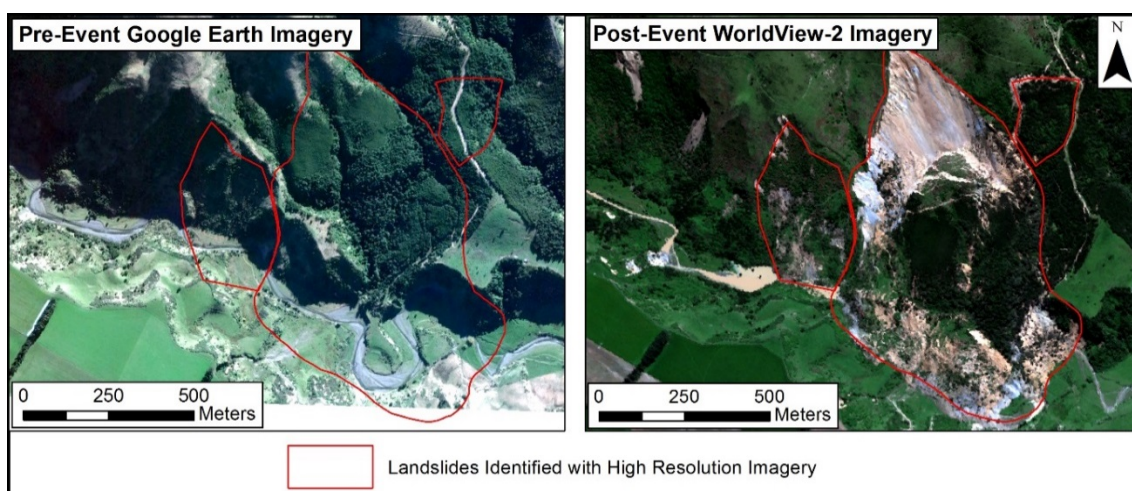


Figure 5. Pre-event Google Earth imagery and post-event Worldview-2 imagery of Leder River landslide from the Kaikoura earthquake (173.2172 S, 42.5848 W).

GNS-UC-GEER team members made effective use of LIDAR scanning to document earthquake effects both inside and outside structures at key locations of interest. Figure 6 shows a LIDAR scan from within Building S37 at CentrePort in Wellington showing an example of the cracking and settlement induced by liquefaction. The floor slab of this building was not pile-supported and settled up to 550 mm relative to adjacent pile-supported structures.

Figure 7a shows measurements of liquefaction-induced settlement across CentrePort along the cross-section line shown in Figure 7c. The deck of King's Wharf, supported on driven timber piles as shown in Figure 7b, underwent lateral displacement due to lateral spreading in the fill behind it, which tilted and split the supporting timber piles. Figure 7d shows the manifestation on the Thorndon Wharf deck of differential settlement between the ground and a buried precast concrete seawall. The LIDAR scans provided point cloud data with which to measure small displacements on the order of centimeters due to liquefaction and lateral spreading, and they supplement SfM models gained via UAV photogrammetry.

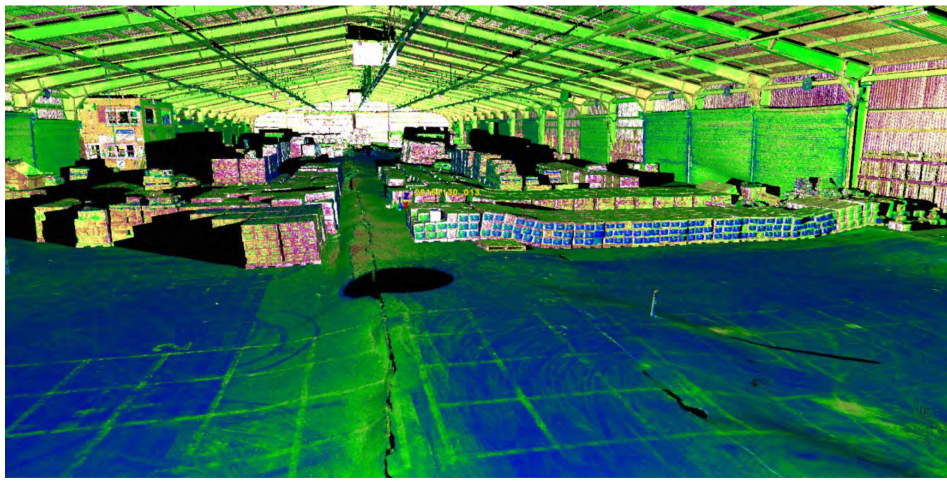


Figure 6. LIDAR scan obtained inside Building S37 in CentrePort of Wellington showing cracking and settlement of the pavement around the buried precast concrete seawall (up to 550 mm of differential settlement occurred) (LIDAR survey by Olsen presented in Cubrinovski and Bray 2017).

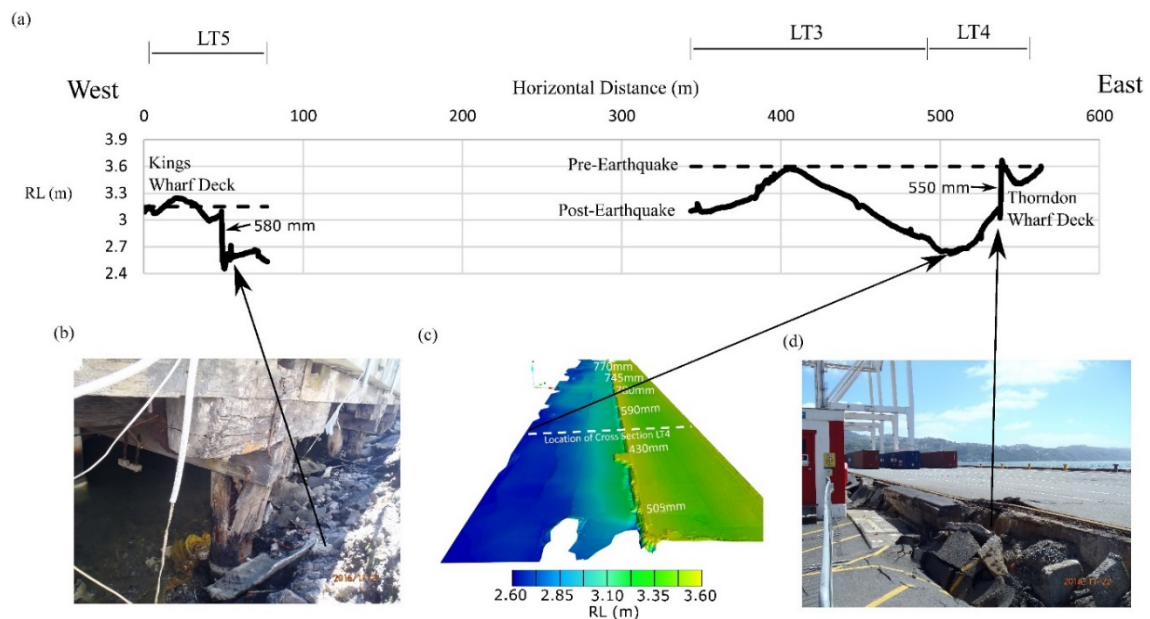


Figure 7. LIDAR scans of wharves at CentrePort Wellington showing deformation from the 2016 Kaikoura earthquake (LIDAR survey by M. Olsen in Cubrinovski et al. 2018).

5.4 2017 Puebla-Mexico City Earthquake and Seismic Site Effects

The September 19, 2017 M_w 7.1 Puebla-Mexico City earthquake affected Mexico City and surrounding areas and produced significant structural damage and over 350 fatalities. Normal fault rupture occurred at a focal depth of 57 km in an intraslab subduction zone 60 km southwest of Puebla and 120 km southeast of Mexico City. Ground motion records indicated a higher frequency content in the soft clay underlying Mexico City than observed during the 1985 Michoacan earthquake. Strong ground shaking measuring intensity level VII on the MMI scale collapsed over 40 multi-story buildings in Puebla and Mexico City. A joint reconnaissance effort between the Universidad Nacional Autónoma de México (UNAM) and GEER took place between September 24 and October 6, 2017 to document the extent of earthquake-related damage and effects. An advance team and a main team documented their findings in a series of GEER-UNAM reports (e.g., Mayoral et al. 2018).

The GEER-UNAM team deployed LIDAR stations and UAVs to survey the extent of damages and performed seismic surveys using tools such as MASW. They used ground-based LIDAR to model the interior and exterior of damaged structures and facilities. In the southern section of Colonia Del Mar, where extensive ground settlement was observed, GEER main team members utilized LIDAR to map ground cracking and ground failure patterns as shown in Figure 8. In Morelos, they used LIDAR to map the damage to the Rio Yautepec Bridge near the towns of Estacas and Yautepec. A 40-m wide landslide occurred adjacent to this bridge, damaging the roadway approach to the bridge and its southwest wing wall. The team gathered UAV imagery of this bridge and stitched the imagery together using SfM technology to create a 3D model of the damaged bridge as shown in Figure 9. The figure shows the landslide-related damage to the bridge as well as the 40 m width of the landslide and tension cracks forming up the slope behind the slide. In total, the GEER main team and advance team conducted UAV surveys at 23 different locations and LIDAR surveys at 5 locations, garnering over 260 GB of image data that allow researchers to continue to analyze damage even after the conclusion of field reconnaissance (Mayoral et al. 2018).



Figure 8. LIDAR model showing ground failure in Colonia del Mar (N19.2851°, W99.0579°; Mayoral et al. 2018).



Figure 9. 3D model of a landslide adjacent to the Rio Yautepec Bridge created using SfM from UAV images (N18.7306°, W99.1194°; Mayoral et al. 2018).

6 FUTURE OPPORTUNITIES

As noted earlier, significant advances have been made in the way post-earthquake reconnaissance is performed. High-resolution digital cameras, UAVs, SfM, LIDAR, and other new technologies are enabling researchers to collect large amounts of quantifiable data. The US NSF-sponsored Natural Hazards Engineering Research Infrastructure (NHERI) activity is making additional technologies available through its *RAPID* facility. Although these data present great opportunities for advancing knowledge and understanding in earthquake geotechnical engineering, they also present challenges. Protocols for utilizing the new technologies are being made available to the hazards community through the NHERI *DesignSafe* cyberinfrastructure (Rathje et al. 2017a) activity, which was originally focused on archiving experimental data. It was recognized that earthquakes and their effects present an equally important opportunity for learning and advancing knowledge. Many of the data collection and data archiving methods developed to document laboratory experiments can capture field observations following earthquakes as part of constructing well-documented case histories.

There are significant opportunities for streamlining the flow of data from initial collection in the field to access by researchers, and subsequent analysis and integration of data. As more data intensive and computation intensive techniques are used to collect field observations of earthquake effects, the challenge becomes how best to archive these datasets for long term use and reuse. This is particularly the case for high resolution point clouds from LIDAR and SfM, although all reconnaissance efforts would benefit from more formal and organized publishing of field data. The *DesignSafe* cyberinfrastructure web platform mentioned previously provides a data repository and data analysis tools that can be used to share and publish reconnaissance data (Rathje et al. 2017a). Reconnaissance data can be published with a citable DOI, and those data can be easily accessed at *DesignSafe*. The GEER reconnaissance reports published on the GEER website will continue to be its legacy contribution; however, the detailed data collected by GEER reconnaissance teams will now be available for future researchers through *DesignSafe*.

Early adoption of advanced technologies for post-disaster reconnaissance should continue to be a focus of post-earthquake reconnaissance activities. Elements of this activity will be facilitated by access to the technology available through the NHERI facilities (e.g., *RAPID* and *DesignSafe*). At the same time, it is recognized that many of the most effective technologies and procedures used currently in post-earthquake reconnaissance efforts were brought forward and demonstrated by creative individuals. The profession should always seek out researchers and practitioners with new technologies that can enhance the quality and quantity of data collected. As has been a requirement for all GEER reconnaissance activities since 1999, all data must be geo-referenced. Not only does this allow for rapid integration of data from multiple different sources but it facilitates the sharing with and utilization by others of data collected by post-earthquake reconnaissance teams.

There is a ripe opportunity to advance documentation of earthquake effects through better utilization of social media data (e.g., Dashti et al. 2014). Data harvested from social media can fill gaps, especially by collecting images of earthquake effects immediately after the event before post-earthquake reconnaissance teams have mobilized. The observations of citizens can help identify features of interest to survey. Data mining techniques could be better utilized during both the preparation for response activities as well as in preparing post-event reports. With the ever-increasing amount of digital data archived and readily available, there are opportunities to improve how reconnaissance activities are planned and executed, as well as how findings are documented and shared.

The primary objectives of post-earthquake reconnaissance activities should remain focused on acquiring the perishable data upon which well-documented case histories can be developed to support follow-on field, laboratory, and numerical studies. Historically, many of these case histories have been event-driven. For example, only by observing the performance of systems and infrastructure in actual events do deficiencies in understanding become evident and lead to further studies. In short, many of the case histories might be described as reactionary to event observations. This will continue as new observations lead to new directions of research. However, the earthquake geotechnical engineering profession should pre-think and pre-stage the full-scale physical experiments of likely future major earthquakes to take full advantages of these opportunities to advance knowledge and reduce the devastating impacts of earthquakes.

As reminder of the importance of post-earthquake reconnaissance as the profession moves forward, two examples of its impact are discussed below:

- Much of the data collected in the reconnaissance efforts following the 2010-2011 New Zealand events were critical to supporting research which has advanced the state-of-the-art in liquefaction evaluation. Examples are the refinement of the Boulanger and Idriss (2016) CPT-based liquefaction triggering procedure, which used New Zealand data to improve its magnitude scaling function (MSF) and fines content (FC) adjustments, and the development of the Bray and Macedo (2017) simplified liquefaction-induced building settlement procedure, which used the building settlement and performance data to calibrate their numerical simulations and to validate the simplified procedure.
- Based on research following the 2010 Darfield earthquake (e.g., O'Rourke et al. 2012), high density polyethylene (HDPE) water mains replaced damaged portions of the water distribution system in the Burwood and Darlington areas of Christchurch. No damage was observed in these HDPE pipelines after the 2011 Christchurch, 13 June 2011, and 23 December 2011 earthquakes, even though this area was subjected to severe liquefaction, with settlement and lateral spreading as high as 3 m. HDPE pipelines installed for earthquake resistance have been proven to perform extremely well when subjected to large liquefaction-induced ground displacements. These developments are extraordinarily important for lifeline earthquake-resistant design and construction.

7 CONCLUSIONS

Recent GEER studies illustrate what effective post-earthquake geotechnical reconnaissance can accomplish. GEER reconnaissance efforts have succeeded in large part because of the value that earthquake geotechnical engineers place on developing well-documented field case histories that form the cornerstone of understanding for their profession. Researchers continue to need to develop improved design and analytical procedures to achieve societal resilience. It is critical that the earthquake geotechnical engineering profession continues to effectively capture the perishable data that enables it to understand which design procedures work well and which do not. With robust field data and observations and the resulting insights and knowledge, earthquake geotechnical engineering researchers can advance key concepts in performance-based earthquake engineering. Knowledge can be advanced through the careful documentation of the geotechnical effects of important earthquakes.

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