Turning Disaster into Knowledge

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ABSTRACT

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 soil deposits built by nature over thousands of years. Furthermore, much of the data generated by a major disaster is perishable, so it is critical that it is collected soon after the 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 design procedures used by geotechnical engineers. Thus, documenting the key lessons learned from major extreme events around the world contributes significantly to advancing research and practice in geotechnical engineering. This is one of the primary objectives of the Geotechnical Extreme Events Reconnaissance (GEER) Association. Post-event reconnaissance and GEER are described in this paper, along with some of GEER's findings from recent reconnaissance efforts. The use of advanced reconnaissance techniques is highlighted, as well as specific technical findings from the 1999 Kocaeli, Turkey earthquake, 2010 Haiti earthquake, 2010 Maule, Chile earthquake, 2010-2011 Canterbury earthquake sequence and 2014 floods that followed it, and the 2014 Oso, Washington landslide.
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1 INTRODUCTION

There have been major improvements in scientific understanding and subsequent advances in geotechnical engineering in the aftermath of significant natural and human-made disasters in urbanized and industrial areas. For example, events that have significantly influenced earthquake engineering include the 1964 Niigata, 1964 Alaska, 1985 Mexico City, 1989 Loma Prieta, 1994 Northridge, 1999 Kocaeli, and 1999 Chi-Chi earthquakes. Other extreme events that have influenced geotechnical engineering include the 1963 Vaiont Dam landslide, the 1966 collapse of the Aberfan colliery spoil tip, the 1976 Teton Dam failure, and the 2001 collapse of the World Trade Center Towers. More recently, the profession has learned much from studies conducted in the aftermath of Hurricanes Katrina (2005) and Gustav (2008), the 2011 Lower Mississippi River floods. Each major disaster potentially provides critical lessons that can save lives in a future event.

Fortunately, severe hazards that have the potential to kill people and destroy infrastructure occur relatively infrequently. Hence, they are referred to as "extreme events." However, they occur frequently enough with the capacity for such severe consequences that society cannot ignore them. Instead, we must learn from them and develop the understanding that will allow engineers to evaluate and to mitigate the effects of future extreme events, such as earthquakes.

In this paper, some of the recent efforts of the U.S. National Science Foundation (NSF)-sponsored Geotechnical Extreme Events Reconnaissance (GEER) Association are chronicled. GEER is one of the world's leading reconnaissance organizations. Although originated as a NSF-funded activity in the United States, GEER includes members worldwide and works closely with other reconnaissance organizations to capture perishable data following an event so the profession can later learn from it.

2 GEER

The NSF-sponsored GEER Association organizes and supports reconnaissance efforts by geotechnical researchers and practitioners after severe natural and human-made disasters (i.e., “extreme events”) and develops techniques to capture perishable data to learn from these events. It distributes findings from these reconnaissance efforts through GEER web-reports, peer-reviewed papers, and technical seminars. The primary objectives of GEER are:

1. Document geotechnical engineering and related effects of important extreme events to advance research and practice.
2. Employ innovative technologies for post-event reconnaissance.
3. Advance the capabilities of individuals performing reconnaissance of extreme events.
4. Train individuals to perform effective reconnaissance and facilitate access to equipment required for sensing and data collection.
5. Develop a coordinated response for geo-researchers to form effective reconnaissance teams and work effectively with organizations that focus on other disciplines.
6. Promote the standardization of measurement and reporting in reconnaissance efforts.
7. Disseminate timely and accurate post-event web-based reports and data.

Since its formation, GEER has made significant advancements with respect to these objectives. Additionally, GEER serves the NSF by identifying important geotechnical issues to study through observing and documenting geotechnical effects in the field after extreme events.

3 SIGNIFICANCE OF POST-EVENT RECONNAISSANCE

Much of the data and information generated by an extreme event 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 data that could advance the state-of-the-art. Geotechnical engineering professionals must respond effectively so that potentially critical lessons are not missed. Additionally, because case histories form the cornerstone of geotechnical engineering more so than other disciplines, geotechnical engineers are uniquely poised to work with other professionals after a major event to document its effects so that we can learn from it and turn information gathered following the disaster into knowledge.

Many of the currently employed analytical methods utilized to evaluate geotechnical hazards, such as liquefaction-induced ground failure and its effects on building and buried utilities performance, rain-induced landslides and their effects on residential areas and transportation systems, and hurricane-induced storm surge and its effects of on levee and coastal protection surface systems, are in need of updating. Often the recommended evaluation and mitigation procedures in engineering practice are based on previously documented case histories that describe both poor and good performance during significant events. For example, prevalent liquefaction triggering procedures are based primarily on the empirical methods delineated in Youd et al. (2001), Seed et al. (2003), and Idriss and Boulanger (2008). Simplified seismic slope and embankment displacement procedures (e.g., Bray and Travasarou 2007, and Rathje and Antonakos 2011) are not used by engineers until they have been shown to capture the observed performance of earth/waste structures during earthquakes. These and other commonly employed engineering procedures require continual re-evaluation and revision as important case histories are documented.

Even more importantly, new unanticipated observations from significant events often define alternative research directions. As an example, the results of recent studies of soil liquefaction, especially those involving soils with a significant amount of fines, have been largely motivated by observations of liquefaction and ground softening documented by NSF-sponsored GEER reconnaissance efforts after earthquakes in Turkey and Taiwan. 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/cyclic ground softening of fine-grained soils and led to important new criteria for evaluating the liquefaction potential of these soils (e.g., Bray and Sancio 2006). Additionally, observations in Taiwan by Stewart (2001) have supported research by Chu et al. (2004) on the liquefaction of fine-grained soils.

If the geotechnical engineering profession is not prepared to look for and find new "geotechnical insights" following future events, important research insights and opportunities will be lost. Additional case histories are required to enhance the profession's understanding of critical geotechnical phenomena. Important advancements are possible through research of these effects in future extreme events if their consequences are captured carefully and comprehensively.

The geotechnical engineering profession has a rich tradition of understanding the need to develop and to apply new technologies and techniques that document in detail the effects of extreme events on urban infrastructure. The significant experience of geotechnical engineers in documenting the effects of natural hazards and their leadership in implementing new technologies in reconnaissance activities, positions them to work closely with other professionals to document the effects of extreme events and to advance the practice of geotechnical engineering through learning the lessons from these disasters.

4 ADVANCES IN RECONNAISSANCE METHODS FOR GEOTECHNICAL EFFECTS

The last decade or so represents a time of unprecedented advancement in the technologies used to document earthquake damage (e.g., Frost and Deaton 2000; Deaton and Frost 2002). The innovative use of personal digital assistants (PDAs) to record earthquake damage resulting from the 1999 Kocaeli, Turkey earthquake allow engineers to collect systematically and analyze carefully observations in a consistent manner. Ground-based lidar (light detection and ranging) mapping technology proved useful in documenting levee damage resulting from storm surge from the 2005 Hurricane Katrina before reconstruction efforts erased physical evidence that proved critical to understanding the potential failure mechanisms involved at levee breach sites (e.g., Seed et al. 2005). Additionally, the use of GoogleEarth™ is revolutionizing the way engineers and scientists merge and convey information. Recent GEER reports have included geo-referencing of photographs and observations of damage using GoogleEarth™. *KMZ* files provide an intuitive way to share key data.

Emerging technologies that will continue to be implemented in future reconnaissance efforts include satellite imaging using various techniques, coordinated military flyovers using advanced imaging capabilities, digital mapping equipment for establishing accurate documentation of ground failure case histories, coordinated use of GPS (Global Positioning System) devices and digital cameras in aerial surveys followed by complementary ground surveys, and survey equipment for documenting the effect of ground failures on constructed facilities. It is anticipated that the utilization of technologies, such as inexpensive ground motion sensors and 3D imaging technologies, will expand significantly in the coming years.

Best practices for performing effective reconnaissance have been delineated in a manual for GEER reconnaissance teams that was developed by Robert Kayen and other members of the GEER Steering Committee (GEER 2014). Soon after an extreme event 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. Areas to investigate in greater depth are identified, and GoogleEarth™ is used to coordinate and record team member activities and their field observations. The data and information that can be collected by post-event reconnaissance teams includes high quality digital photographs of damage from aircraft and from the ground. Aerial photographs taken after the event can be compared to those from existing databases to help define damage patterns that can provide invaluable insights. Reconnaissance activities may include geologic and damage mapping, shear wave velocity profiling using the multi-channel analysis of surface waves (MASW) technique, and dynamic cone penetration tests (DCPT) at liquefaction sites, as shown in Fig. 1. All observations can be documented digitally and positioned accurately using GPS coordinates allowing integration into reports.

Besides photographic documentation that records images of damaged and undamaged facilities and systems, advanced techniques, such as lidar, can be used to help document more completely ground deformation across wide areas (Kayen and Collins 2012). Ground-based lidar has been used successfully 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 Shiroiwa (White Rock) landslide, a large landslide produced by the shaking of 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 Fig. 2. The lidar image is analogous to a detailed digital photograph wherein each pixel is identified with its x, y, and z location.

Figure 1. Field activities in Haiti: geologic and damage mapping, MASW testing, and DCPT testing

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

Remote sensing, via spaceborne or airborne sensors, is another tool that has emerged as a crucial component of documenting the effects of natural disasters. Remote sensing represents the acquisition of data using sensors not in direct physical contact with the area being investigated, and includes optical satellite imagery, synthetic aperture radar (SAR), and lidar. 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. Very high resolution (VHR) satellite imagery was used to document the distribution of landslides from the 2004 Niigata-ken Chuetsu earthquake (Rathje et al. 2006) and to investigate the influence of geologic, topographic, and seismologic conditions on urban damage patterns from the 2010 Haiti earthquake (Rathje et al. 2011). 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).

SAR represents an active remote sensing technique in which the reflections of transmitted radar signals are measured. Because of the active source, SAR can acquire imagery at night or through clouds, which are attractive features for acquiring data as quickly as possible after an extreme event. In addition to the collected imagery, SAR data allows for advanced analytical techniques, such as radar interferometry (InSAR), which can provide precise measurements of ground deformation. Specifically, InSAR has been successful in measuring aseismic and coseismic slip across faults (e.g., Sandwell et al. 2002) and documenting the spatial and temporal distribution of landslide movements (Hilley et al. 2004).

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 well-documented case histories that drive the development of many of the empirical procedures used in geotechnical 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 later 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, yet 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 currently all damage observations, whether made in the field or via remote sensing techniques, are geo-referenced to standard cartographic projections using GPS.

Existing techniques can also be better utilized in a coordinated manner to obtain quantitative data on ground failure and building performance after an extreme event. For example, using a modified version of the Coburn and Spence (1992) rapid survey of structural damage and the ground failure index presented in Bray and Stewart (2000), reliable damage data were obtained in the city of Adapazari after the 1999 Kocaeli, Turkey earthquake before damaged buildings were razed or repaired. These data (an example is shown in Fig. 3) proved to be invaluable for focusing later in-depth studies. These data allowed investigators, such as described in Sancio et al. (2002), to correlate the occurrence of ground failure with particular ground conditions, as illustrated in Fig. 4.

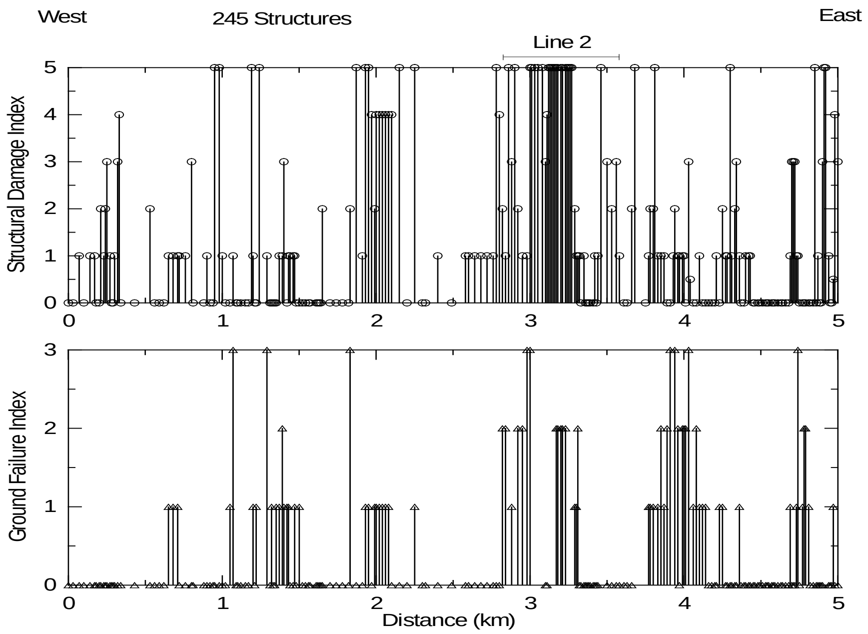

Figure 3. Structural Damage Index, which Ranges from D0 (no observed damage) to D5 (complete collapse of a story or building), and Ground Failure Index, which Ranges from GF0 (no observable ground failure) and GF3 (significant building penetration of more than 25 cm or 3 degrees tilt) on Line 1 in Adapazari, Turkey (Bray and Stewart 2000)

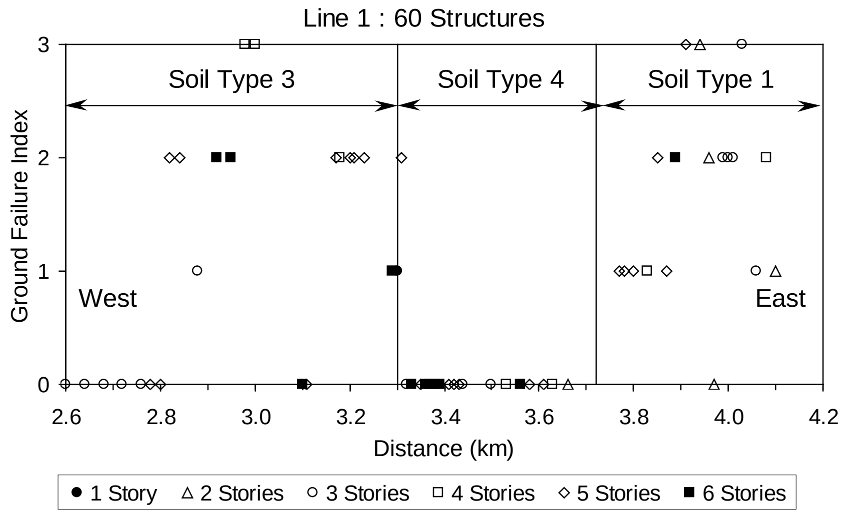

Figure 4. Correlation of Ground Failure and Soil Type on Line 1 in Adapazari, Turkey. Soil Types 1 and 3 contain liquefiable silt deposits, but Soil Type 4 does not (Sancio et al. 2002)

5 ILLUSTRATIVE GEER RECONNAISSANCE EFFORTS

5.1 1999 Kocaeli, Turkey Earthquake and Fine-Grained Soil Liquefaction

Until recently, engineers relied upon the so-called Chinese criteria (i.e., Youd et al. 2001) to assess if fine-grained soils were potentially liquefiable. Using evidence of liquefaction of fine-grained soils from well-documented observations after earthquakes that occurred over the last 15 years, such as the 1999 Kocaeli, Turkey earthquake, the liquefaction criteria of Bray and Sancio (2006) and Idriss and Boulanger (2008) have replaced the Chinese criteria. This work was possible largely as a result of observations made by GEER team members following recent earthquakes and research studies that followed from observations made during the initial reconnaissance efforts.

The Bray and Sancio (2006) criteria for identifying soils that are potentially susceptible to liquefaction are based primarily on cyclic testing of “undisturbed” specimens of silts and clays from the city of Adapazari, Turkey. Research funding was provided for a comprehensive experimental program that included over 100 cyclic triaxial tests and 10 cyclic simple shear tests after field observations made following the 1999 Kocaeli earthquake could not be explained using the Chinese criteria (Bray et al. 2004). Cyclic testing of a wide range of soils found to liquefy in Adapazari during the Kocaeli earthquake confirmed that these fine-grained soils were susceptible to liquefaction. Bray and Sancio (2006) found that it is not the amount of “clay-size” particles in the soil; rather, it is the amount and type of clay minerals in the soil that best indicate liquefaction. Thus, plasticity index (PI) is a better indicator of liquefaction susceptibility. Bray and Sancio (2006) found that soils with PI ≤ 12 and with water content to liquid limit ratios (w_c/LL) ≥ 0.85 were susceptible to liquefaction when strongly shaken as evidenced by a dramatic loss of strength resulting from increased pore-water pressure.

5.2 2010 Haiti Earthquake and Seismic Site Effects

The 2010 M_w 7.0 Haiti earthquake represents one of the most devastating earthquakes in history in terms of human impact, with an estimated 200,000 or more deaths and millions left homeless. NSF supported a GEER team to investigate the influence of geotechnical conditions on the devastation in Haiti (Rathje et al. 2010). The team was able to take advantage of various remote sensing data sources during its reconnaissance, including high-resolution aerial photography and lidar acquired by the World Bank. They performed geologic and damage mapping, shear wave velocity profiling using the multi-channel analysis of surface waves (MASW) technique, and dynamic cone penetration tests (DCPT) at liquefaction sites.

The power of merging field data and observations from remote sensing was fully realized by the work done by the GEER team after the field reconnaissance. Damage data derived by UNOSAT (http://www.unitar.org/unosat/) from aerial photography was compared with the team's field damage data for accuracy assessment, then integrated with geologic, topographic, and shear wave velocity information to evaluate the influence of these conditions on the damage distribution (Fig. 5). Complex, but clear, relationships between geologic/shear wave velocity conditions and topographic conditions were identified, which highlighted the important need to better understand these influences (Rathje et al. 2011).

An outcome of this work is that the GEER team returned to Haiti in November 2010, under the support of the U.N. Development Programme, to share with the Haitian Ministry of Public Works the data collected and to give a two-day short course on geotechnical earthquake engineering. The short course was attended by over 50 engineers and geologists, and in a small way helped Haiti with its rebuilding efforts.

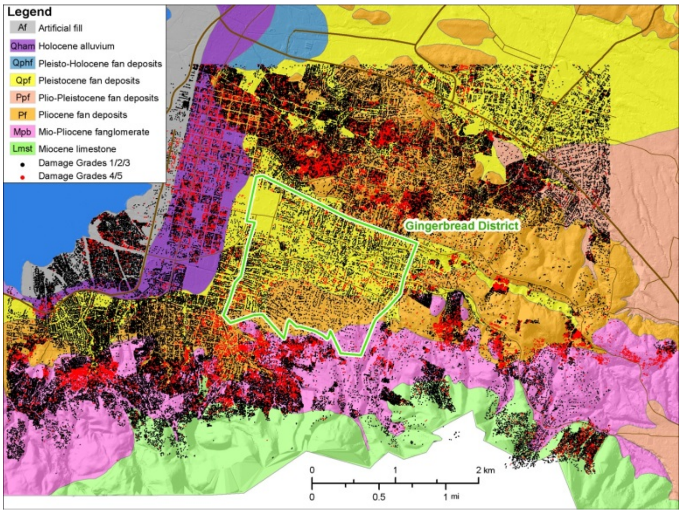

Figure 5. Integration of geologic, topographic, and damage data for Port-au-Prince, Haiti (Rathje et al. 2011)

5.3 2010 Chile Earthquake and Earth Structure Performance

The February 27, 2010 Maule, Chile earthquake (M_w = 8.8) is the seventh largest earthquake to occur since 1900. Its effects were felt along 600 km of the central Chilean coast. Field observations suggest that tectonic displacement of the hanging wall produced uplift of over 2 m in some coastal regions and subsidence of up to 1 m in others. The tsunami initiated by the rupture devastated parts of the coast and killed hundreds of people. Strong shaking lasted for over a minute in some areas, and widespread damage occurred in some cities. A large number of significant aftershocks contributed additional damage to an already fragile infrastructure.

Post-event reconnaissance conducted by GEER documented soil liquefaction at many sites, as wellas the associated ground failure and lateral spreading (Bray and Frost 2010). Of special interest were the effects of liquefaction on the built environment. Several buildings were damaged significantly due to foundation movements resulting from liquefaction. Liquefaction-induced ground failure displaced and distorted waterfront structures, which adversely impacted the operation of some of Chile's key port facilities. Critical lifeline structures, such as bridges, railroads, and road embankments, were damaged by ground shaking and ground failure. The damage to some sections of Ruta 5, the primary North-South highway in Chile, was pervasive, which disrupted supply traffic following the event (Moehle and Frost 2012).

Most earth retention systems, such as retaining walls and basement walls, proved to be inherently robust and performed well during the earthquake. Landslides and other large earth movements were not pervasive, which appears to have resulted from native slopes that are generally composed of competent earth materials and the relatively low groundwater levels present at the end of the dry season. Most dams, levees, and mine tailings dams also performed well. Several key earth structures experienced some distress, and in one case a liquefaction-induced tailings dam failure produced a flow slide that killed four. Pre- and post-event satellite imagery of the tailings impoundment is shown in Fig. 6.

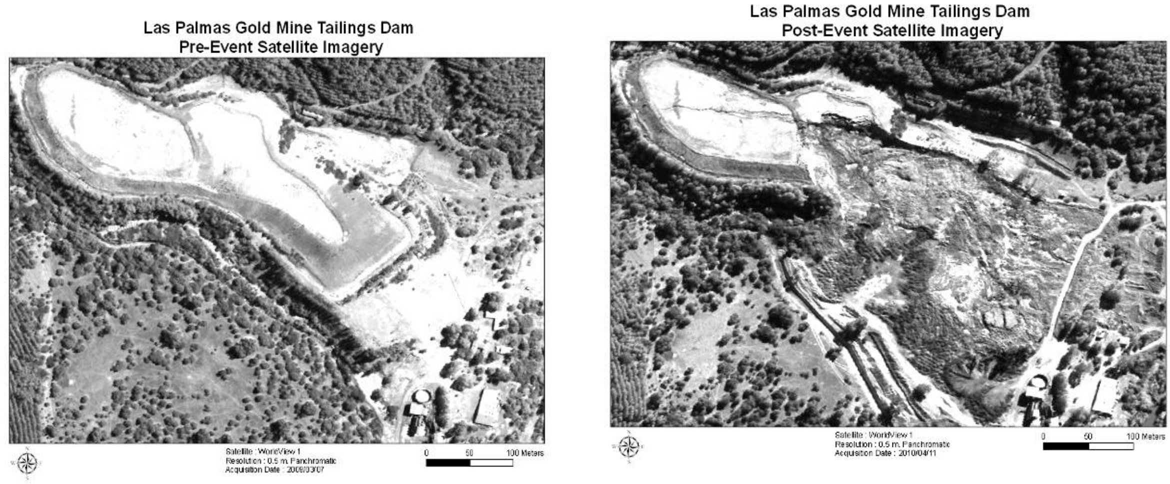

Figure 6. Pre- and post-earthquake satellite images of failed tailings impoundment from the 2010 Maule, Chile earthquake

5.4 2011 Tohoku, Japan Earthquake and Cascading Events

The 2011 Tohoku, Japan earthquake event is already shaping practice with the numerous ground motion recordings at sites throughout Japan for both the M_w=9.0 subduction event and its many aftershocks. U.S. GEER researchers partnered with Japanese researchers to conduct several focused surveys of damage (e.g., Ashford et al. 2011). Although Japanese researchers are carrying out the bulk of the research and will be sharing lessons to be learned over the next decade with the international community, several important Japan-U.S. research initiatives will also provide useful insights. For example, co-locating several CPTs with standard penetration test (SPTs) boreholes at liquefaction sites will enable the extensive Japanese database of borehole information with SPTs to be leveraged effectively to enhance CPT-based liquefaction triggering procedures. This research is critically important for examining the effects of duration from this large magnitude event. Detailed studies of seismic site response at liquefaction sites that recorded ground motions at the surface and within the profile will also provide useful insights.

The Tohoku event was significant for a number of reasons, not the least of which was that it was the largest recorded and studied event in the modern era. The unprecedented amount of sensor information available (e.g. strong motion, and video recording) provided some of the most critical pre-event baseline as well as post-event information about the earthquake and the subsequent tsunami. This baseline data is critical to allow meaningful interpretations of the damage patterns observed following an event beyond the high quality perishable data collected by GEER and similar teams.

Another factor that contributes to the significance of the Tohoku event is that it clearly showed the importance of predicting and understanding the importance of cascading events. While a significant earthquake was the trigger in the Tohoku event, an equally significant tsunami followed by flooding and the failure of generators at the Fukushima Daiichi nuclear power plant led to uncontrolled release of radiation. This may be the most significant impact of the entire event with the most far reaching implications, not just for residents of the immediate area surrounding the facility but for the future of nuclear energy on a global scale.

5.5 2010-11 Canterbury, New Zealand Earthquakes and 2014 Christchurch Floods

The Canterbury, New Zealand earthquake sequence during 2010-2011 has yielded the most comprehensive data to date of the integrated effects of multiple earthquakes and liquefaction episodes, including the locations and types of damage for underground lifelines in Christchurch, thousands of residential structures, and scores of commercial buildings. Field observations are complemented by high-resolution airborne lidar measurements of lateral and vertical surface movements for multiple earthquakes and hundreds of liquefaction surveys and geodetic measurements. A key finding from the reconnaissance efforts was the documentation that HDPE water mains sustained no damage when subjected to more than 2 m of ground movement (O'Rourke et al. 2012).

GEER teams responded to this sequence of earthquakes (Green and Cubrinovski 2010; Cubrinovski et al. 2011). As is typically the case with earthquakes outside of the United States, this effort was a collaborative partnership between New Zealand and U.S. researchers. As there is more to learn from this extensive database of observations gathered and fieldwork performed (e.g., thousands of cone penetration tests (CPTs) have been advanced by the New Zealand government to characterize the ground), it is likely that several follow-on research studies will yield important findings that will advance the state-of-practice in geotechnical earthquake engineering.

In many cases, cascading events are thought of those that happen within relatively short time periods following natural disasters. For example, a tsunami may follow an earthquake with minutes or hours. Likely, severe aftershocks following an earthquake may occur for a period of weeks or at most months. Less attention has been historically paid to follow-on or cascading events which may not occur for several years or more. In other cases, these follow-on events are considered multi-hazard effects as opposed to cascading events, both from an occurrence as well as consequence prediction perspective. In this context, floods which followed about 3 to 4 years after the Christchurch earthquakes represented a unique opportunity to evaluate whether there were in fact, important implications on the flooding and associated consequences that occurred in early 2014. In particular, given the significant earthquake-induced consequences of the 2010-2011 earthquake series including tectonic deformations, liquefaction-induced settlements and lateral spreading, as well as associated subsequent sedimentation of rivers and other waterways as nature sought to reach new equilibrium conditions following the earthquake, GEER deployed a team to record and evaluate the degree to which such the lingering effects of the earthquakes influenced the flooding impact (Allen et al. 2014).

5.6 2012 Hurricane Sandy and Coastal Protection Systems

Hurricane Sandy was unprecedented in scale and impact on the Northeast region of the United States and in particular for a large number of coastal communities along the New Jersey and New York coasts. The storm brought focused attention to the potential consequences of climate change and exposed the fragility of our modern urban infrastructure to this phenomenon. It specifically highlighted the vulnerability of many of our infrastructure systems to a new norm for extreme events, both in terms of their location and magnitude. The storm produced severe coastal damage, as well as major flooding in areas susceptible to coastal inundation. Critical subsurface infrastructure experienced flood levels well beyond their design criteria. A GEER team deployed after the event documented significant information over a wide area to ensure that critical observations of perishable information were captured within the context of the characteristics of the event. The resulting disruption to everyday business, education, transportation and logistics, amongst other factors, was both unexpected and at the same time, an exceptional reminder of what happens when humankind challenges nature.

As the world begins to grasp and prepare for similar events resulting from further climate change, this event will serve as an exceptional reminder, as well as case history, with implications for engineering, policy and socio-economic sciences. The consequences of this event are already propagating through engineering, science and legislative corridors as the importance of enhancing the resiliency of our infrastructure to both withstand, as well as rapidly recover from, such an extreme natural event is being appreciated. Various approaches are now being discussed and evaluated. Engineers, architects, planners and developers are exploring the merits of both short-term enhancements to fortify existing infrastructure systems as well as long term approaches to build more resilient infrastructure.

5.7 2014 Oso, Washington Landslide and Large Debris Flows

The Oso, Washington landslide killed 43 people and injured dozens more when it flowed rapidly across the valley floor and the neighborhood of Steelhead Haven on the morning of 22 March 2014 (Keaton et al. 2014). The landslide completely destroyed the Steelhead Haven neighborhood, as well as several adjacent homes. Approximately 600 m of Washington State Highway 530 was buried under up to 6 m of debris, which closed this major transportation route for over 2 months. The landslide caused significant economic losses of more than $50 million. The overall size of the Oso Landslide was approximately 7.6 million cubic meters. It was the deadliest landslide in U.S. history. Due to the many lives lost and the long run-out distance of the debris flow (i.e., > 1 km), GEER mobilized a team to document perishable data so that insights could be developed (Keaton et al. 2014).

A post-event aerial image of the Oso landslide is shown in Fig. 7. Additionally, Fig. 7 displays an elevation difference map using data from lidar surveys performed before and after the Oso landslide. Topography before and after the Oso landslide were captured in a series of high-resolution airborne lidar surveys taken before the 2006 landslide, in 2013, and after the 2014 Oso landslide (Keaton et al. 2014). Analysis of these lidar data sets allows for high resolution mapping of the landslide source area and depositional zones. These data are invaluable for documenting the characteristics of the large landslide/debris flow. Additionally, the lidar surveys clearly show similar types of large prehistoric debris flows that traveled across the valley floor. Thus, the lidar surveys help set the context for determining the uniqueness of the Oso landslide and for characterizing the landslide hazard of the slopes along the North Fork of the Stillaguamish River within the valley.

The Oso landslide initiated within an approximately 200-m-high hillslope comprised of unconsolidated glacial and colluvial (i.e., previous landslide) deposits (Keaton et al. 2014). The slope had slid several times since the 1930's and is also the site of an ancient landslide. The most recent prior activity took place in 2006, when a smaller landslide moved across the North Fork Stillaguamish River. The 2006 landslide traveled over 100 m, but came to rest before reaching Steelhead Haven. However, the 22 March 2014 Oso landslide transitioned to a catastrophic debris flow that traveled more than a kilometer across the valley floor and buried Steelhead Haven. Although it occurred on a clear, sunny day, the landslide occurred soon after a three-week period that was marked by unusually high levels of rainfall. Rain and stream gauges in the vicinity and NEXRAD Doppler weather radar data made it possible to estimate the amount of antecedent rainfall that occurred before the landslide (Keaton et al. 2014). Such data are invaluable for identifying the causative mechanism of the landslide. Additional investigations are underway, including geologic studies and geotechnical subsurface investigations, to help researchers understand the initiation mechanism of the landslide and as importantly, the reasons why this time it flowed across the valley floor. The GEER report is an invaluable resource in ongoing studies to discern the cause of the Oso landslide.

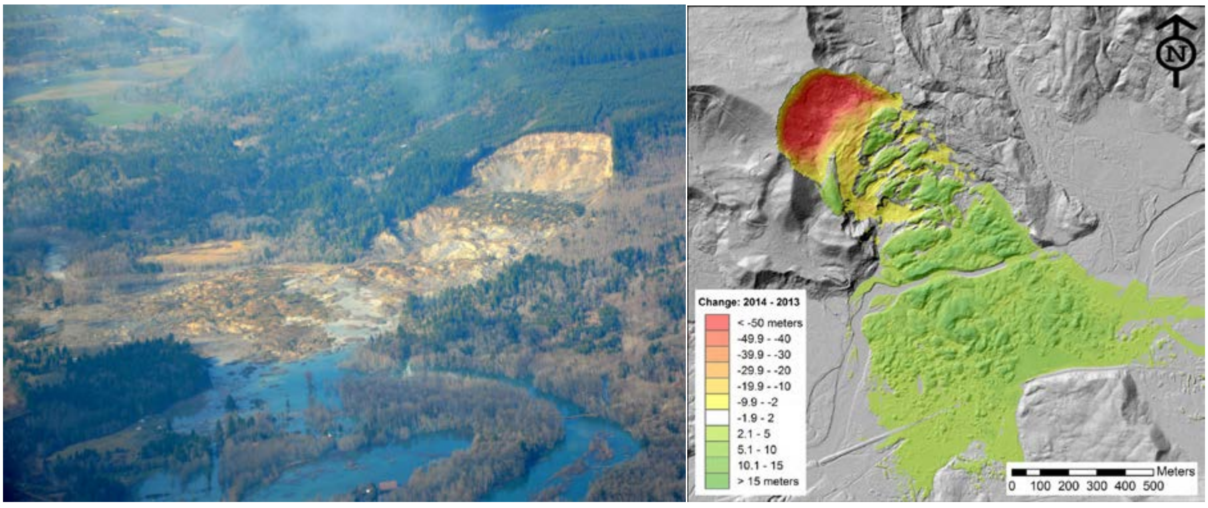

Figure 7. Aerial image of Oso, Washington landslide and elevation differences based on pre- and post-event lidar surveys (courtesy of the Washington Dept. of Transportation and Keaton et al. 2014)

6 CONCLUSION

Understanding and knowledge can be advanced through the documentation of the effects of extreme events. Recent GEER post-event reports illustrate what effective post-event geotechnical engineering reconnaissance can accomplish. These efforts succeeded in large part because of the value that geotechnical engineers place on learning from disasters and on developing well-documented case histories that form the cornerstone of understanding for the geotechnical engineering profession. The death and destruction resulting from recent events emphasize society's need to improve its resilience. Unfortunately, extreme events will happen. It would be unfortunate if the geotechnical engineering profession did not capture the perishable data that enables it to understand which design procedures result in good performance and which procedures still need improvement. With this enhanced understanding and with robust empirical data, researchers can advance the practice of geotechnical engineering. The formation of GEER and the willing participation of geotechnical engineers have allowed this goal to be realized for the benefit of the profession and society.

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The GEER Association currently has over 250 members and 4 organizational partners. GEER is led by a Steering Committee (SC) that is currently composed of Jonathan Bray, Chair (UC Berkeley), David Frost, Co-Chair (Georgia Tech), Ellen Rathje, Co-Chair (Univ. of Texas at Austin), Scott Anderson (Federal Highway Admin.), Robert Gilbert (Univ. of Texas at Austin), Laurie Johnson (Laurie Johnson Consulting|Research), Robert Kayen (USGS), Jeff Keaton (AMEC Environment and Infrastructure), and Nick Sitar (UC Berkeley). The GEER SC receives guidance from a broad-based Advisory Panel (AP) consisting of a larger group of prominent hazard engineers and scientists that includes members of organizations that participate actively in post-event reconnaissance (such as the U.S. Geological Survey, the Earthquake Engineering Research Institute, and the U.S. Army Corps of Engineers). Members of the GEER AP are: J.P. Bardet, R. Boulanger, M. Comerio, M. Crawford, C. Davis, R. DesRoches, C. Edwards, E. Fielding, R. Green, L.F. Harder, Jr., T.L. Holzer, A. Kammerer, S.L. Kramer, W. Lettis, S. Mahin, J.R. Martin, II, S. Nikolaou, R.S. Olsen, T.D. O'Rourke, A. Rosinski, P. Somerville, K. Tierney, H. Yeh, T.L. Youd, and Y. Wang. The GEER Recorder, Christine Beyzaei, assists teams in performing reconnaissance activities and in preparing reports, develops website features and posts web-based reports, and maintains the records of the GEER Association. GEER is described further at: http://www.geerassociation.org/.

REFERENCES

Allen, J., Davis, C., Giovinazzi, S., and Hart, D., Eds. [2014]. "Geotechnical & Flooding Reconnaissance of the 2014 March Flood Event Post 2010-2011 Canterbury Earthquake Sequence, New Zealand," a report of the NSF- Sponsored GEER Association Team, primary authors: Allen et al., GEER-035, Ver. 1, June 19, 2014 http://www.geerassociation.org/.

Ashford, S., et al. [2011]. "Geotechnical Reconnaissance of the 2011 Tohoku Japan Earthquake**,"** Quick Report 1: GEER-025a (April 5, 2011): http://www.geerassociation.org/.

Bray, J.D., and Stewart, J. P. [2000]. "Damage Patterns and Foundation Performance in Adapazari," Chapter 8 of the *Kocaeli, Turkey Earthquake of August 17, 1999 Reconnaissance Report*, in *Earthquake Spectra* Journal, Suppl. A to Vol. 16, EERI, pp. 163-189.

Bray, J.D. and Sancio, R.B. [2006]. "Assessment of the Liquefaction Susceptibility of Fine-Grained Soils," *J. of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 132, No. 9, pp. 1165-1177.

Bray, J.D. and Travasarou, T. [2007]. "Simplified Procedure for Estimating Earthquake-Induced Deviatoric Slope Displacements," *J. of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 133, No. 4, pp. 381-392.

Bray, J.D. and Frost, J.D., Eds. [2010]. "Geo-engineering Reconnaissance of the 2010 Maule, Chile Earthquake," a report of the NSF- Sponsored GEER Association Team, primary authors: Arduino et al., GEER-022, Ver. 2, May, 2010, http://www.geerassociation.org/.

Chu, D., Stewart, J., Lee, S., Tsai, J.S., Lin, P.S., Chu, B.L., Seed, R., Hsu, S.C., Yu, M.S., Wang, M. [2004]. "Documentation of soil conditions at liquefaction and non-liquefaction sites from 1999 Chi–Chi (Taiwan) earthquake," *Soil Dynamics & Earthquake Engrg.*, V. 24, pp. 647–657.

Coburn, A. and Spence, R. [1992]. *Earthquake Protection*. John Wiley & Sons, West Sussex, England.

Deaton, S.L., and Frost, J.D. [2002]. "Integrated Digital Earthquake Reconnaissance", *7th U.S. National Conference on Earthquake Engineering*, CD-ROM.

Frost, J.D., and Turel, M. [2011]. "Satellite, Airborne and Ground Based Imaging of Earthquake Damage and Geotechnical Hazards", *Journal of Highway & Transportation Research & Development*, Vol. 28, No. 6, pp. 41-48.

Geotechnical Extreme Events Reconnaissance (GEER) Association [2014]. Website for Dissemination for GEER Activities, http://www.geerassociation.org/.

Green, R.A. and Cubrinovski, M., Eds. [2010]. "Geotechnical Reconnaissance of the 2010 Darfield (New Zealand) Earthquake", GEER Association Report No. GEER-024, (http://www.geerassociation.org/GEER_Post%20EQ%20Reports/Darfield%20New%20Zealand_2010/Cover_Darfield_2010.html)

Cubrinovski, Green, R.A., and Wotherspoon, L., Eds. [2011]. "Geotechnical Reconnaissance of the 2011 Christchurch (New Zealand) Earthquake", GEER Report No. GEER-024, (http://www.geerassociation.org/GEER_Post%20EQ%20Reports/Christchurch_2011/Cover_Christchurch_2011.html)

Hilley, G., Burgmann, R., Ferretti, A., Novali, F., and Rocca, F. [2004]. "Dynamics of Slow-Moving Landslides from Permanent Scatterer Analysis," *Science,* 304, pp. 1952-1955.

Idriss, I.M., and Boulanger, R.W. [2008]. *Soil Liquefaction During Earthquakes*. Earthquake Engineering Research Institute, MNO-12, Oakland, CA.

Kayen, R., Pack, R., Bay, J., Sugimoto, S., Tanaka, H. [2006]. "Terrestrial-LIDAR Visualization of Surface and Structural Deformations of the 2004 Niigata Ken Chuetsu, Japan, Earthquake," in *Earthquake Spectra* Journal, Suppl. S1 to Vol. 22, EERI, pp. S147-S162.

Kayen, K. and Collins, B. [2012]. "Taking the Measure of Disaster with Terrestrial Laser Scanning," Geo-Strata, Geo-Institute of ASCE, 14-20.

Keaton, J., Wartman, J., Anderson, S., Benoit, J., deLaChapelle, J., Gilbert, R., and Montgomery, D.R. [2014]. "The 22 march 2014 Oso Landslide, Snohomish County, Washington," a report of the NSF- Sponsored GEER Association Team, primary authors: Arduino et al., GEER-036, Ver. 1, 22 July 2014, http://www.geerassociation.org/.

Kelson, K., Bray, J., Cluff, L., Harder, L., Kieffer, S., Page, W., Perkins, W., Rix, G., Roblee, C., Sitar, N., Wells, D., Wright, R., and Yashinsky, M. [2001]. "Fault-Related Surface Deformation," Chapter 3 of the *Chi-Chi, Taiwan, Earthquake of September 21, 1999 Reconnaissance Report*, in *Earthquake Spectra* Journal, Suppl. A to Vol. 17, EERI, pp. 19-36.

Moehle, J.P. and Frost, J.D., Eds. [2012] Special Issue on the 2010 Maule, Chile, Earthquake, in Earthquake Spectral J., EERI, V28(S1).

O'Rourke, T.D., Jeon, S.-S., Toprak, S., Cubrinovski, M., and Jung, J.K. [2012]. "Underground Lifeline System Performance during the Canterbury Earthquake Sequence," 15 WCEE, Lisbon, Portugal, Sept., CD-ROM.

Rathje, E.M., Crawford, M., Woo, K., and Neuenschwander, A. [2005]. "Damage Patterns from Satellite Images from the 2003 Bam, Iran Earthquake," *Earthquake Spectra,* Earthquake Engineering Research Institute, 21(S1), pp. S295-307.

Rathje, E.M., Kayen, R., and Woo, K.-S. [2006]. "Remote Sensing Observations of Landslides and Ground Deformation from the 2004 Niigata Ken Chuetsu Earthquake," *Soils and Foundations*, Japanese Geotechnical Soc., 46(6), pp. 831-842.

Rathje, et al. [2010]. "Geotechnical Engineering Reconnaissance of the 2010 Haiti Earthquake," a report of the NSF- Sponsored GEER Association Team, GEER-021, Feb., http://www.geerassociation.org/.

Rathje, E., Bachhuber, J., Dulberg, R., Cox, B., Kottke, A., Wood, C., Green, R., Olson, S., Wells, D., and Rix, G. [2011]. "Damage Patterns in Port-au-Prince during the 2010 Haiti Earthquake," *Earthquake Spectra,* Earthquake Engineering Research Institute, 27(1), p. S117-S136.

Rathje, E.M. and Antonakos, G. [2011]. "A Unified Model for Predicting Earthquake-Induced Sliding Displacements of Rigid and Flexible Slopes," *Engineering Geology,* 122, 51-60, doi:10.1016/j.enggeo.2010.12.004.

Sancio, R. B., Bray, J. D., Stewart, J. P., Youd, T. L., Durgunoglu, H.T., Onalp, A., Seed, R. B., Christensen, C., Baturay, M. B., and Karadayilar, T. [2002]. "Correlation Between Ground Failure And Soil Conditions In Adapazari, Turkey," *Soil Dynamics and Earthquake Engineering* Journal, October-December 2002, V. 22 (9-12), pp 1093 – 1102.

Sandwell, D., Sichoix, L., and Smith, B. [2002]. **"**The 1999 Hector Mine earthquake, Southern California: Vector near-field displacements from ERS InSAR," *Bulletin of the Seismological Society of America*, 92(4), 1341-1354.

Seed, R.B., Cetin, K.O., Moss, R.E.S., Kammerer, A.M., Wu, J., Pestana, J.M., Riemer, M.F., Sancio, R.B., Bray, J.D., Kayen, R.E., and Faris, A. [2003]. "Recent Advances in Soil Liquefaction Engineering: A Unified and Consistent Framework," 26th Annual ASCE Los Angeles Geotechnical Spring Seminar, Keynote Presentation, Long Beach, CA.

Seed, R.B., P.G. Nicholson, R.A. Dalrymple, J. Battjes, R.G. Bea, G. Boutwell, J.D. Bray, B. Collins, L.F. Harder, J.R. Headland, M. Inamine, R.E. Kayen, R. Kuhr, H. Mashriqui, J. M. Pestana, F. Silva-Tulla, R. Storesund,

S. Tanaka, J. Wartman, T. Wolff, L. Wooten and T. Zimmie. [2005]. “Preliminary Report on the Performance of the New Orleans Levee Systems in Hurricane Katrina on August 29, 2005,” Report No. UCB/CITRIS - 05/01, Univ. of Calif., Berkeley, Nov. 17.

Stewart, J.P. (Coordinator), Chu, D., Seed, R., Ju, J-W, Perkins, W., Boulanger, R., Chen, Y-C., Ou, C-Y, Sun, J., and Yu, M-S. (Contributors) [2001] “Soil Liquefaction,” Chapter 4 of the Chi-Chi, Taiwan, Earthquake of September 21, 1999 Reconnaissance Report, in *Earthquake Spectra* Journal, Suppl. A to Vol. 17, EERI, 2001, pp. 37-60.

Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Finn, W.D. Liam, Harder, Jr., L.F., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcuson, III, W. F., Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., and Stokoe, II, K.H. [2001]. “Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils,” Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 127, No. 10, pp. 817-833.

Youd, T.L., Bardet, J.P., and Bray, J.D. [2000]. Kocaeli, Turkey Earthquake of August 17, 1999 Reconnaissance Report, in *Earthquake Spectra* Journal, EERI, V16(A).