Earthquake science in resilient societies

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Key Points:

- The level of seismic risk depends on a societal investment in earthquake science
- Multidisciplinary investigations involving earthquake scientists and engineers greatly reduce casualties in earthquakes
- Recent examples highlight the utility of earthquake science in building resilient societies, and the need for further research to reduce seismic risk

Abstract

Earthquake science is critical in reducing societal vulnerability to a broad range of seismic hazards. Evidence-based studies drawing from several branches of the Earth sciences and engineering can effectively mitigate losses experienced in earthquakes. Societies that invest in this research have lower fatality rates in earthquakes and can recover more rapidly. This commentary explores the scientific pathways through which earthquake-resilient societies are developed. We highlight recent case studies of evidence-based decision making and how modern research is improving the way societies respond to earthquakes.

1 What are the risks and costs of earthquakes?

Strong ground shaking in earthquakes has resulted in millions of deaths in the last century, with many millions more projected in the future [*Holzer and Savage*, 2013]. For many, destructive landslides and tsunami, fault ruptures that tear through unlucky homes, flooding and liquefaction in recurring aftershocks, fires, and disease can add up to sustained economic losses—let alone numerous casualties—that reach far beyond the initial earthquake and ground shaking. Since the beginning of just the 21st century, earthquakes and their secondary effects have caused over 700,000 deaths, millions of injuries, and hundreds of billions of dollars in damage [*Bilham*, 2009; *Quigley and Duffy*, 2016]. Worldwide, approximately 20-25% of earthquake-related deaths are due to secondary effects, and some of the largest death tolls in natural disasters have been due to these phenomena (e.g., ~227,000 deaths in the 2004 Indian Ocean tsunami) [*Marano et al.*, 2010].

As Earth's population continues to grow, so too does the fraction of the population exposed to earthquake hazards. On a global scale, earthquake-related fatalities and seismic risk have only increased through time [*Bilham*, 2009]. This trend is largely due to the increased urbanization, exposure, and vulnerability of economically developing regions prone to earthquakes. From 1900-2009, approximately 80% of all earthquake shaking related fatalities were caused by just 25 earthquakes in 11 countries [*Jaiswal et al.*, 2009]. The earthquake cost is more economic in the developed world, where less casualties occur in events of similar intensity due to investment in earthquake science, engineering, and education [*Bilham*, 2009; *Jaiswal and Wald*, 2011]. Even in well-prepared regions, however, the scale of the economic toll can prolong or prevent recovery.

There is no immunity to earthquakes or related hazards, but scientists and engineers who study earthquakes can provide solutions that avert disaster and reduce the burden quakes have on society. This commentary explores the multidisciplinary pathways through which we have come to understand earthquakes and what constitutes an earthquake-resilient society. We provide a case study that highlights how this science has progressed along with promising avenues for future research.

2 What causes earthquakes and how are they measured?

Earthquakes are caused by rapid displacement on faults and the sudden release of accumulated strain in the form of seismic waves. These seismic waves cause ground shaking that collapse buildings, damage infrastructure, and can cause widespread landsliding in mountainous terrain. Earthquakes have been problematic for as long as humans have been building structures, even to the point that some argue for tipping-points in which the collapse of entire civilizations were catalyzed by major earthquakes [c.f. *Sintubin*, 2011]. But it wasn't until 1910 that Harry Fielding Reid, an American geologist studying the 1906 San Francisco earthquake, formulated a hypothesis by which earthquakes occur, therefore allowing earthquake hazard to be evaluated. Reid used seismology, structural geology, and survey data to postulate a mechanism for earthquakes called *elastic rebound*: that the slow buildup of forces on either side of a locked fault eventually results in its sudden rupture and release of seismic energy [*Reid*, 1910]. At the time, Reid used seemingly disparate bits of information to develop the now well-accepted *elastic rebound theory*, some 60 years before the acceptance of the *theory of plate tectonics*. We now recognize *plate tectonics* as the foundational principle of modern geology, which forms the basis of our understanding of where and how often earthquakes occur.

As Reid envisioned, the study of earthquakes requires information and expertise from several geologic and engineering disciplines (Table 1). Geodesists and geomorphologists use high-precision survey data from global positioning systems (GPS), satellite-based radar, lidar, and image analysis to identify active faults at the Earth's surface and monitor how quickly they are accumulating tectonic strain on 'human' timescales. Paleoseismologists date and measure previous episodes of fault motion and analyze the geologic record of earthquake ground shaking (e.g., earthquake-induced landslides, or ancient tsunami deposits preserved on land) in prehistoric earthquakes. Seismologists detect modern earthquakes and map out the deeper structure of the Earth. Engineers measure the response of the Earth's surface to shaking and can design structures that are resistant to different levels and frequencies seismic shaking. Hazard modelers aggregate this data with geographic and historical information to more reliably predict the spatial distribution and magnitude of destruction in large events.

3 How do we plan for earthquakes?

So, what use are all of these fields and the troves of data they produce? A common public misconception is that the end result is, or should be, earthquake prediction—precise dates, times, locations, and magnitudes of impending earthquakes. In fact, the lack of reliable quake precursors have infamously drawn geologists into legal problems [*Cartlidge*, 2015], propped up less-than-scrupulous hypotheses regarding the predictive power of astrology [*Stahl*, 2011], and led to an unfortunate public view that earthquake science is the 'ambulance down in the valley' rather than as a series of fences at the top (or nets along the way).

The purpose of the work of earthquake scientists and engineers is to mitigate unnecessary damage and loss of life. Researchers and practitioners identify likely geologic hazards, inform policy on where and how to build structures, determine how to best divide resources and response teams in the aftermath of quakes, and educate policy makers and the public on how to best prepare for earthquakes. Detailing the contribution that each field makes towards these larger societal goals (Table 1) is outside the scope of this overview, but we hope to briefly highlight the hallmarks of good earthquake science through the hand lens of recent earthquakes in New Zealand.

4 Two examples from New Zealand

4.1 The 2010-2011 Canterbury earthquakes

New Zealand lies on a major tectonic plate boundary and is no stranger to large earthquakes. In 2010-2011, a magnitude 7.1 (M7.1) earthquake and its M6.3 aftershock dealt a devastating blow to one of its largest cities, Christchurch. Due to a “perfect storm” of geologic conditions, the M6.3 aftershock resulted in some of the strongest ground motions ever recorded—nearly 5 times those that killed over 100,000 people in the 2010 Haiti earthquake. Despite comparable ground motion in these two events, 185 people died in Christchurch; 115 of those from the collapse of a single building that was not designed to code [*Royal Commission*, 2012].

Both earthquakes occurred on previously unknown faults, which were buried beneath thick alluvial plain sediments [*Quigley et al.*, 2010] and volcanic rocks. Because individual faults could not be identified from surface mapping, scientists planned for a ‘distributed source’ M7 earthquake in the region instead of an earthquake on a single fault line [*Stirling et al.*, 2008]. As anticipated, widespread liquefaction and flooding occurred throughout the city and was one of the most damaging components of the earthquake. The potentially hazardous areas were well documented, and largely identified as such, prior to the earthquake. Restrictions on the locations of buildings and infrastructure with engineered improvements to the ground will greatly improve the resilience of these areas during future earthquakes. Although economic recovery in Christchurch is still incomplete 6 to7 years later, prior scientific data greatly mitigated what could have been a much worse outcome. Research conducted in the aftermath of this event has also spawned some of the best case studies of faulting, rockfall, soil liquefaction, and hazard management ever [*Massey et al.*, 2014; *Potter et al.*, 2015; *Quigley et al.*, 2016].

4.2 The 2016 Kaikoura earthquake

In November 2016, a larger M7.8 earthquake struck New Zealand's South Island. Recently published data indicate that it was one of, if not the most, complex earthquakes ever documented. At least 12 faults and more fault segments ruptured in quick succession, resulting in ground motions exceeding that of gravity and tens of thousands of landslides [*GeoNet*, 2016]. Approximately 200 significant landslides dammed or continue to dam rivers [*GeoNet*, 2016]. The earthquake ruptured across a 170 km stretch of faults about midway between New Zealand's capital Wellington and Christchurch. Despite the widespread faulting, strong shaking, landslides, and tsunami, only two people are reported to have died - one from a building collapse, the other from a heart-attack.

We would be remiss to claim that the complexity of this earthquake was fully anticipated by geologists. However, it is a testament to the robustness and diversity of science that goes into seismic hazard assessments, engineering design codes, hazard planning, in addition to the low population density in the worst-affected area, that so few casualties occurred. And, despite its complexity, the magnitude and location of this event was not unexpected. Emergency management systems (generally) worked. The rapid collection of data from an international network of engineers and scientists, led by the Institute of Geological and Nuclear Sciences (GNS) in New Zealand, allowed for a coordinated and targeted humanitarian response. Continued scientific monitoring of landslides, landslide dams, and flood hazards are underway and have provided valuable data to the public, transportation authorities and civil services. Probabilistic aftershock forecasts have been continuously updated by GNS since November and have further informed the timeline of response and recovery efforts. This is how earthquake-resilient societies operate—on data, research, and planning.

Table 1: Disciplines, goals, and outcomes of earthquake science

Discipline	**Description**	**Goals as applied to earthquake science**	**Examples of tractable research questions**
Paleoseismology	Assessment of prehistoric earthquakes and their environmental effects	Identify active faults; Estimate the recurrence interval of large earthquakes throughout recent geologic time; Anticipate the magnitudes of earthquakes on faults; Anticipate the response of Earth's surface to faulting and strong ground motions	Where will earthquakes occur in the future? How big will the earthquakes be, on average? Where have secondary hazards (tsunami, landslides, liquefaction) occurred in the past?
Seismology	Assessment of the rates, size and location of modern earthquakes; the structure of the Earth; and the response of Earth's surface to seismic waves	Identify active faults; Monitor the location and frequency of earthquakes through time; Determine the structure of the Earth; Determine the response of different sites to incoming seismic waves	What is the annual frequency of destructive earthquakes in a region? What is the probability of a magnitude 6 aftershock in the next month?
Fault/rock mechanics;	The physics of how rocks	Understand how earthquakes initiate and	How does rock type influence

Engineering geology	deform and fail under stress	the controls on how large they can grow; Assess slope stability at the surface	the size of the largest earthquake on a fault? Where are landslides likely to occur when subjected to shaking?
Geodesy	Remote sensing of Earth processes through space and time	Identify active faults; Quantify rates and processes that lead to earthquakes	Where are large aftershocks likely to occur? Which faults a currently accumulating seismic strain and likely to rupture?
Tectonic geomorphology and structural geology	Numerical, field, and lab-based science for the tectonic evolution of a region over all timescales	Identify the processes and spatial distribution of faulting, slope failure, and erosion through geologic time, and quantify their rates and interactions	How do earthquake-induced landslides contribute to erosion? How do fault slip rates and earthquake hazards change through time?
Geotechnical engineering (sub-discipline of civil engineering)	The behavior and response of Earth materials	Determine the response of rocks and soils to seismic waves and seismic soil-structure interaction; Predict locations and type of ground failure (landslides, liquefaction, rock fall)	Which areas and what types of sediment are prone to liquefaction? How do soils amplify seismic waves?
Civil engineering/structural engineering	Design, construction and maintenance of built environment	Reduce the vulnerability of structures to fault displacements, seismic shaking, and other secondary hazards	How can we prevent flooding due to earthquake subsidence? How can we isolate a building's foundation to prevent shaking-induced collapse?
Hazard and disaster management	Predict and mitigate negative outcomes of earthquakes on society	Model economic losses and fatalities for response and recovery operations; predict spatial distribution of adverse impacts on infrastructure; Interface with policy makers	Where are the most fatalities expected to focus response and relief efforts? What is modelled effect of earthquake-induced landslides on transportation networks?

5 How can science better prepare us for earthquakes in the future?

Although we are unlikely to ever be able to predict earthquakes, we can improve our resilience to them. New datasets, technologies, computational power, and continued investment in STEM advance our ability to react quickly to events and prioritize resources. For example, new methodologies can provide rapid assessment of the location and size of earthquake-induced landslides from high-resolution, satellite-derived elevation models of the Earth [*Gallen et al.*, 2014]. We can continue to improve our models of how ruptures ‘jump’ onto other faults to generate larger earthquakes [*Stahl et al.*, 2016; *Hamling et al.*, 2017]. We can prevent avoidable catastrophes in the United States, where nearly 50% of the population faces some degree of earthquake hazard (Fig. 1) [*Jaiswal et al.*, 2015], and in developing nations where the seismic risk of exposed populations is far greater [*Tucker*, 2013]. This work requires a concerted effort from many scientific disciplines to provide the means to build resilient societies and educate the public and policy makers.

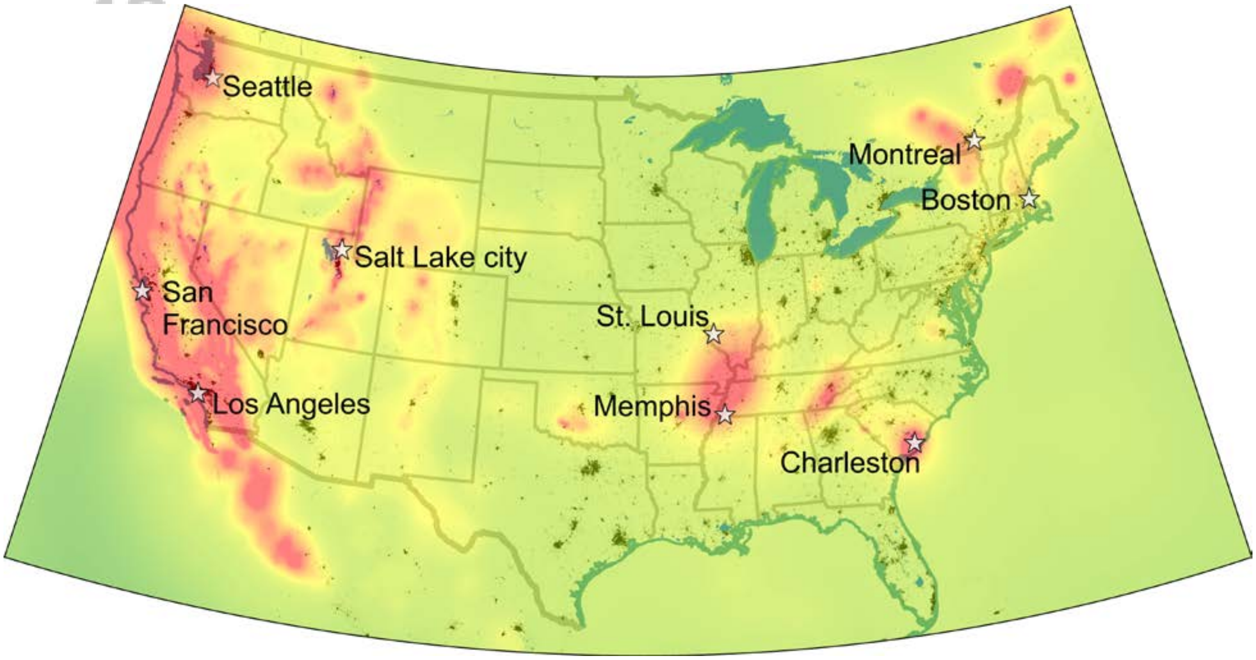

Figure 1: Seismic hazard of the conterminous United States. This map shows a 2% probability of exceeding a mapped peak ground acceleration (PGA, green to red colors) in 50 years. The darkest red colors represent PGAs of approximately 0.5-1.0 g. This map is a simple visual representation of the 2014 USGS hazard map (available at https://earthquake.usgs.gov/hazards/hazmaps/conterminous/) and should not be used for hazard purposes. Major population centers shown with stars and population density is shown in black and white (black=areas of densest population; data from GPWv4 by Center for International Earth Science Information Network, 2016).

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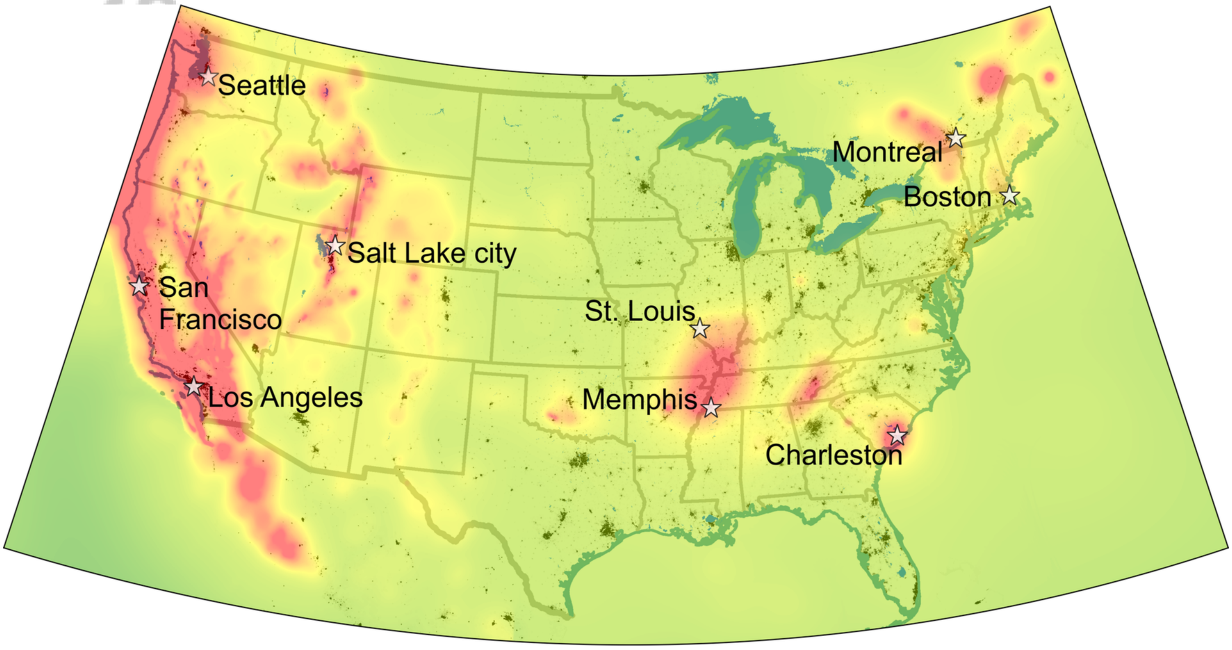

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