OPINION

Resilience by Design: Bringing Science to Policy Makers

INTRODUCTION

No one questions that Los Angeles has an earthquake problem. The "Big Bend" of the San Andreas fault in southern California complicates the plate boundary between the North American and Pacific plates, creating a convergent component to the primarily transform boundary. The Southern California Earthquake Center Community Fault Model has over 150 fault segments, each capable of generating a damaging earthquake, in an area with more than 23 million residents (Fig. 1). A Federal Emergency Management Agency (FEMA) analysis of the expected losses from all future earthquakes in the National Seismic Hazard Maps (Petersen *et al.*, 2014) predicts an annual average of more than $3 billion per year in the eight counties of southern California, with half of those losses in Los Angeles County alone (Federal Emergency Management Agency [FEMA], 2008). According to Swiss Re, one of the world's largest reinsurance companies, Los Angeles faces one of the greatest risks of catastrophic losses from earthquakes of any city in the world, eclipsed only by Tokyo, Jakarta, and Manila (Swiss Re, 2013).

The last large earthquake in Los Angeles, the M_w 6.7, 17 January 1994, Northridge earthquake happened the day before abstracts were due for the last meeting of the *Seismological Society of America* held in Pasadena. It took 45 min to get the first estimate of location and magnitude ("about 6 and a half in the northwest San Fernando Valley") and 2 hr to locate the first aftershock, a failing of the computer systems that eventually led to the development of TriNet and the first broadband network in the United States (Hauksson *et al.*, 2001). When FedEx delivered more than 400 abstracts for that meeting, most of the seismologists in Pasadena had not slept in 30 hr. The consequences to Los Angeles were more significant than lost sleep. Thirty-five people lost their lives from earthquake damage (even more from heart attacks during the earthquake), and total damage is estimated at $20 billion and another $49 billion in economic loss, the costliest natural disaster in the United States prior to Hurricane Katrina (Risk Management Solutions, 2004).

Although the scientific and engineering communities learned much from that event and significant changes were made in the International Building Code for new construction, the Northridge earthquake did not lead to any significant effort in southern California to reduce the existing earthquake vulnerability. The proposals to require retrofitting of the dangerous nonductile concrete and soft-first buildings became instead voluntary ordinances that have led to less than 1% compliance. The potential for widespread loss of life and financial disruption is understood to exist, but the time scale is long, the costs are large, and the degree to which the losses are preventable is not well understood. Earthquake mitigation is often seen as a sure political loss. If an earthquake does not happen before the end of the elected official's term, they will look like they wasted resources. If one does happen, the mitigation efforts have probably not yet been fully implemented, and they will look ineffective (Los Angeles Downtown News, 2014).

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As we approach the next meeting of *SSA* to be held in Pasadena in April 2015, Los Angeles is moving in a new direction. The city of Los Angeles entered a Technical Assistance Agreement with the U.S. Geological Survey (USGS) to use the science developed about the probable consequences of future earthquakes to create a long-term plan to improve its seismic resilience. Under this agreement, I spent the year in the Mayor's office, working with a team of more than a dozen senior staff to apply the results of a century of research in the science and engineering of earthquakes to an analysis of the city's vulnerabilities and assessment of the implications of possible approaches to reduce the losses. From this, the Mayor has proposed 18 actions to increase the city's resilience through ordinances (by the City Council), executive action, and partnership activities (Los Angeles, 2014).

This article summarizes the scientific basis for the plan, how the partnership came about, the process for developing the plan, and lessons learned for other scientists and communities that want to connect scientific research to policies for community improvement.

FOUNDATIONAL SCIENCE

The assessment of the severity of the earthquake risk for Los Angeles relied on the ShakeOut Scenario (Jones *et al.*, 2008). This scenario of a plausible magnitude 7.8 earthquake details the consequences of an earthquake on the southern San Andreas fault, the fault most likely to produce a great earthquake in the conterminous United States (Field *et al.*, 2013). The scenario is itself a synthesis of the research conducted for decades to understand the earthquake hazards and risk in southern California.

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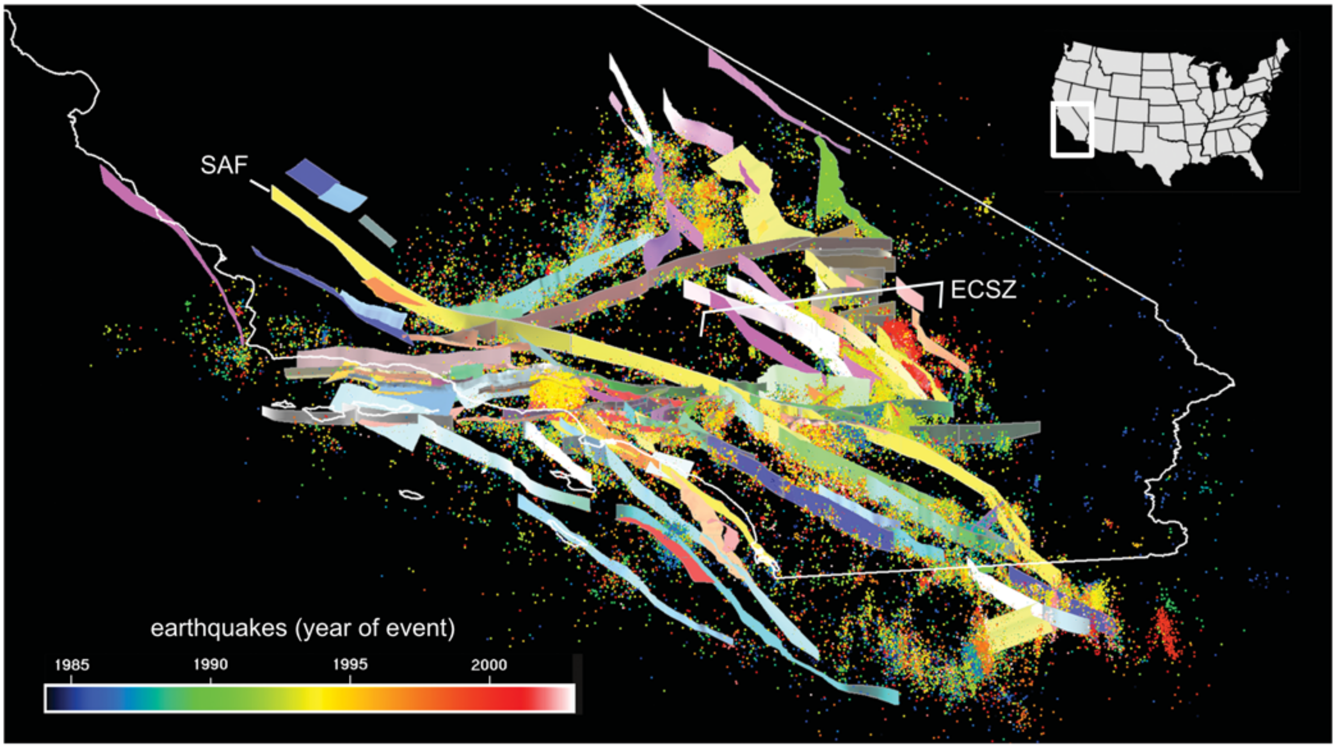

▲ **Figure 1.** Perspective view of fault segments in the Southern California Community Fault Model and seismicity 1984–2004 (fig. 1 from Plesch *et al.*, 2007).

The southern San Andreas fault has generated earthquakes of the size of the ShakeOut scenario on average every 100–150 yr, but in the portion of the fault that ruptured in the ShakeOut Scenario, the last earthquake happened more than 300 years ago (Philibosian *et al.*, 2011). Earthquakes on faults closer to the city will cause more intense damage in parts of Los Angeles, but this very likely San Andreas fault earthquake happens over a larger area and strains our regional capabilities through the scale of the damage. The ShakeOut model predicts ground motions of modified Mercalli intensity IX over thousands of square kilometers and strong ground motions for several tens of seconds in most of the major basins (Fig. 2). The most significant triggered hazards are landslides, fault offsets disrupting lifeline corridors, and triggered fires. If Los Angeles is ready for this likely earthquake, it can handle most others as well.

The magnitude 7.8 ShakeOut earthquake scenario estimated about 1800 deaths and $213 billion of economic losses across southern California (Jones *et al.*, 2008). These losses include shaking damage ($47.7 billion), fire ($65 billion), business interruption costs ($96.2 billion), and traffic delays ($4.3 billion). This scenario has identified five major areas of loss:

1. Older buildings built to earlier standards
2. Nonstructural elements and building contents that are generally unregulated
3. Infrastructure crossing the San Andreas fault
4. Business interruption from damaged infrastructure, including telecommunications, and especially water systems
5. Fire following the earthquake

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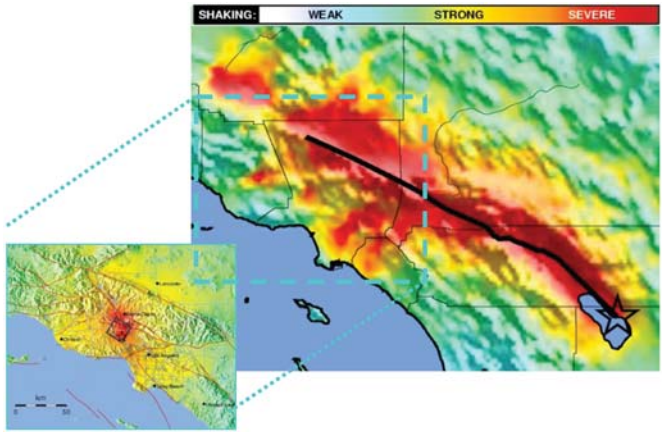
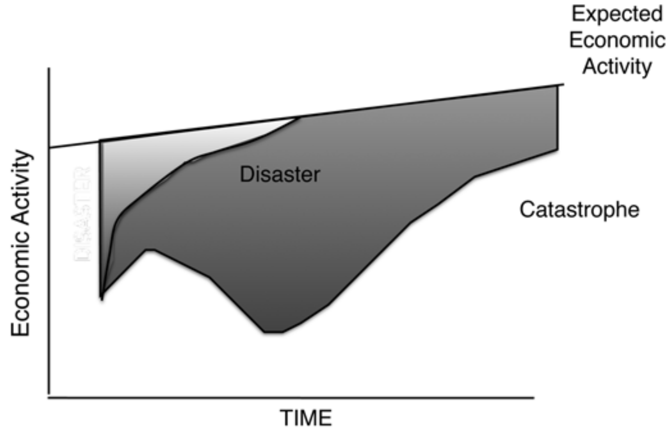
Earthquakes pose a much smaller risk to our lives than many other risks in life in southern California; those 1800 fatalities are less than the number of people who will die in traffic accidents in Los Angeles County in just seven years (Los Angeles County Department of Public Health, 2011). However, the relative risk that earthquakes pose to our pocketbooks is much greater. In Los Angeles County, the expected annualized earthquake loss from all earthquakes is over $1.5 billion, representing one quarter of the total direct loss from earthquakes facing the Nation (FEMA, 2008).

For Los Angeles, as the second most populous city in the United States with a gross domestic product (GDP) of nearly $81 billion (Bureau of Economic Analysis, 2013) and home to the largest port of the United States, economic consequences from a large earthquake would be devastating and could generate unforeseeable rippling effects beyond the city boundaries. Regions consist of cities and municipalities that are geographically and politically defined yet linked by interdependent economies, shared natural resources, and integrated transportation systems. A large earthquake affecting the city of Los Angeles



▲ **Figure 2.** ShakeMaps of the instrumental intensity of earthquake shaking in the 1994 magnitude 6.7 earthquake, and predicted for a magnitude 7.8 earthquake on the southern San Andreas fault, at the same scale.



▲ **Figure 3.** A schematic representation of the impact of a disaster on a regional economy, adapted from Perry *et al.* (2008).

impacts Los Angeles County, California, and the Nation as well.

In spite of this potential for devastating financial losses, California has primarily addressed earthquakes as a problem solely of life safety. The philosophy of the building code is that the financial decision of how much to invest in a building's strength is an individual owner's decision to make, and they have the right to choose a building so weak that it is a complete financial loss after the earthquake, as long they do not kill someone in the process. Thus, even the most current building code requires only a life safety standard for the design earthquake (an earthquake with a 10% chance of occurring in the next 50 yrs) and collapse prevention with the potential for some life loss in the maximum credible earthquake (a 2% chance of occurring in the next 50 yrs; Liel *et al.*, 2010). The result is an urban environment designed to be a financial catastrophe in the aftermath of expected, predictable future earthquakes.

When the biggest earthquakes occur, we face a potentially even greater loss from depression of the regional economy. When a damaging earthquake strikes there is an immediate drop in economic activity (Fig. 3). If outside money can be brought in to start repairs quickly, if the infrastructure comes back into service without a long delay, the recovery will be quicker and the regional economy can return to its expected level within a few years. In the largest earthquakes, and when recovery is delayed by political or financial complications, economic activity may not recover for several decades creating financial losses much greater than those in the earthquake itself, a situation we term a catastrophe.

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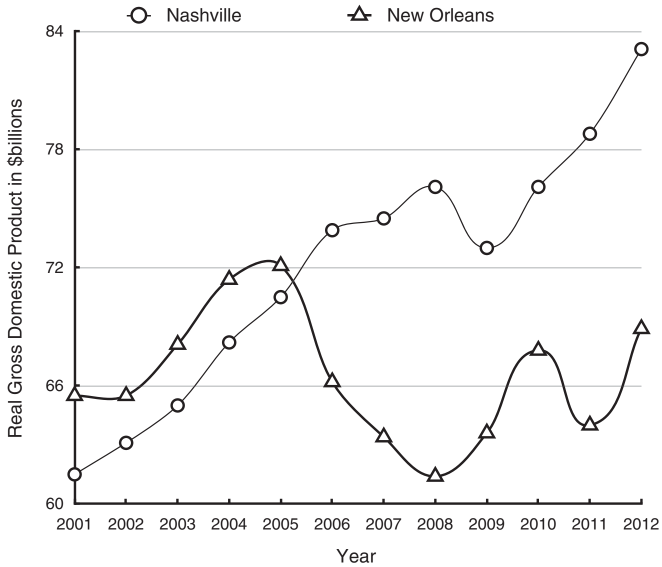
Hurricane Katrina was the greatest disaster the United States has weathered to date. In August 2005, the hurricane caused over 1800 deaths and an estimated $108 billion in direct damages in both Louisiana and Mississippi. Thousands of homes and businesses were destroyed, with debris from these ruined buildings remaining on the ground long after the storm waters had receded (Knabb *et al.*, 2005). Yet even with all of this direct damage, one of the most chilling effects of the storm is how it severely reduced long-term populations in affected areas. From July 2005 to June 2006, 237,000 people migrated away from Louisiana (Olshansky, 2006). By 2014, census data showed that only 100,000 of those people had returned (Corey and Deitch, 2011). This disruption is reflected in the economic activity in the New Orleans area (Fig. 4). The GDP of New Orleans was larger than that of Nashville, a similar sized community 500 miles away, before Hurricane Katrina struck in 2005. Since then, New Orleans has lost ground, and by 2012 had a GDP $15 billion/yr smaller than Nashville. The cumulative lost GDP for those 7 yrs exceeds the total direct loss in the hurricane itself.

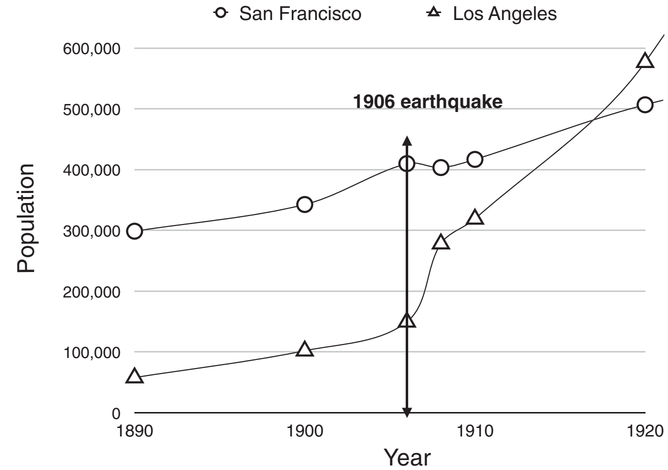
A similar long-term economic depression faced San Francisco after the great San Andreas earthquake of 1906. The economic disruption from the earthquake immediately reduced U.S. GDP by 1.5%–1.8%. Most of the loss was covered by British insurance companies. The capital outflow prompted the Bank of England to raise interest rates and discriminate against American finance bills. British bank policy pushed the United States into recession and set the stage for the 1907 financial crisis (Odell and Weidenmier, 2004). In 1905, San Francisco was the sixth largest city in the United States with a population of 400,000 (U.S. Geological Survey [USGS], 2014). Over the next two decades as other American cities grew several fold, San Francisco lost population at first and then had only limited growth (Fig. 5).

CREATION OF THE COOPERATIVE PROJECT

The ShakeOut scenario was the first product of the USGS Multi Hazard Demonstration Project (MHDP). That project brought



▲ **Figure 4.** The gross domestic product of the Nashville, Tennessee, and New Orleans, Louisiana, metropolitan area per year. Data source: U.S. Bureau of Economic Analysis, Google Data (https://www.google.com/publicdata/explore?ds=a7jenngfc4um7_&hl=en&dl=en#!ctype=l&strail=falsebcs=d&nselm=h&met_y=real_gdp&ind_y=false&rdim=metro&idim=metro:35380:34980&ifdim=metro&hl=en_US&dl=en&ind=false).



▲ **Figure 5.** The population of the cities of San Francisco and Los Angeles (U.S. Census Data). The population of Los Angles grew five-fold in the decade after the 1906 earthquake struck San Francisco.

together engineers and physical and social scientists to engage in interdisciplinary research on topics requested by policy makers in southern California and created a dialog between scientists and policy makers that has continued. The most obvious result of this collaboration has been the continuing activities of the annual ShakeOut drill that began with the ShakeOut scenario (Jones *et al.*, 2008), but also includes a variety of partnerships with utilities, public works agencies, and others.

Separately, ongoing collaborations among building officials, seismologists, and engineers in San Francisco developed through a nine-year process into a *Community Action Plan for Seismic Safety* adopted by the city of San Francisco (City and County of San Francisco, 2013). That plan led to the first local ordinance requiring retrofit of soft-first story apartment buildings in San Francisco. There was considerable interest in this effort in Los Angeles, which led to the first meeting between city officials and the USGS in October 2013 to discuss what steps Los Angeles could take. Those discussions led to the creation of the Technical Assistance Agreement for seismic resilience planning in 2014.

In negotiating the scope of the Agreement, we acknowledged that addressing every possible vulnerability would be too large a task. We defined the primary goals of seismic resilience to be to:

- protect the lives of our citizens during earthquakes
- improve the capacity of the city to respond to earthquakes
- prepare the city to recover quickly after an earthquake
- protect the economy of the city and all of southern California

We then used the results of the ShakeOut scenario study to identify those areas that could be addressed with policies of the city of Los Angeles and that would have the greatest impact on those four goals. From the five major areas of loss described above, we identified four areas to be addressed by the city:

1. Pre-1980 nonductile reinforced concrete buildings
2. Pre-1980 soft-first story buildings
3. Water system infrastructure, including impact on firefighting capability
4. Telecommunications infrastructure

The first two elements primarily address the biggest threats to life safety. Almost all deaths in earthquakes result from failure of human construction, and through the application of stronger building code requirements we have reduced much of the risk to our lives. Most of the risk we now face comes from the harsh reality that no building code in the world is retroactive. The collapse of the new Olive View Hospital in the San Fernando earthquake of 1971 showed the fragility of nonductile reinforced concrete buildings, but only the buildings that received the strong shaking in the northern San Fernando Valley were damaged and removed (Benfer and Coffman, 1974). An estimated 1400 similar buildings remain elsewhere in the city (Anagnos *et al.*, 2012). The 1994 earthquake revealed the problems with soft-first story construction with the collapse of the Northridge Meadows Apartments and the loss of 49,000 housing units (Public Policy Institute of California, 2006), but an estimated 14,000 buildings of this type still exist in the city. The ShakeOut Scenario of a southern San Andreas earthquake predicts the collapse of 1500 buildings, mostly soft-first story and nonductile concrete, causing almost 700 fatalities and tens of thousands of other casualties (Jones *et al.*, 2008).

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The infrastructure (water and telecommunications) elements address the economic vulnerability. The ShakeOut scenario model identifies the water system as the utility most vulnerable to earthquake damage (Jones *et al.*, 2008), and that damage is the single largest cause of business disruption after the earthquake, closing businesses and making it impossible for residents to stay in their houses. Earthquakes can disrupt water services in many ways. The city of Los Angeles gets more than 80% of its water from outside the region through four aqueducts that all cross the San Andreas fault. To use the water, it must be distributed to residences and businesses through water pipes that comprise some of the oldest infrastructure in the city. Some parts of the system need power for pumps. If the water pressure is too low because of breaks in pipes or loss of power, contaminants enter the system and the water is no longer potable. Many water lines run near sewer lines and contemporaneous breaking of both greatly increases the contamination issues.

In addition to service and direct economic loss, damage to water pipe infrastructure impairs the city's ability to fight fires, with the risk of exponential increases in the losses if the fires cannot be controlled. In several cases, great earthquakes in urban areas have spawned super-conflagrations where the damage in the fires eclipses the direct losses from the earthquake. The most catastrophic was the Great Kanto earthquake of 1923 that triggered fires that destroyed most of Tokyo and killed almost 150,000 people, 40,000 from the fires alone (James, 2002). Closer to home, the 1906 San Francisco earthquake led to fires that burned much of the city (USGS, 2012). The 1994 Northridge earthquake triggered 110 fires large enough to require the fire department, and the damage to water pipes made it more difficult to fight the fires (Beall, 1997).

The rise of the Internet has moved telecommunications from an amenity to a critical lifeline of our society and economy. The last very damaging earthquake in California, the 1994 magnitude 6.7 Northridge earthquake, occurred at the dawn of the Internet era, before the first Internet browser, before the formation of the World Wide Web Consortium, and before cellular devices were in popular use (World Wide Web Consortium, 2014). Today, 90 percent of all adults in the United States own a mobile phone (Pew Research Center, 2014). A large earthquake is likely to cause significant disruption of these services (Jones *et al.*, 2008), and any longer-term disruption of these services will impede recovery, amplifying economic losses. Analysis of communication systems in disasters (Kwasinski, 2010) has shown that the cause of system failures has been, in order of frequency, overloaded capacity from too many calls, loss of power, failure of backup power, and damage to equipment and towers at local sites.

The work with Los Angeles has been a closer collaboration with policy makers and elected officials than any previous experience in my career as a scientist. The result has been proposals for some of the biggest shifts in seismic policy ever seen in southern California.

PROCESS

The creation of this plan for seismic resilience was a year-long collaboration among policy makers, technical experts, and stakeholders from the community. The policy makers were primarily from the Mayor's staff. Senior staff from all divisions of the Mayor's office met weekly through the year. An important part of my role was to engage the relevant technical experts. To address the issues posed by poor buildings, a Mayor's Technical Task Force was convened that included leaders of the practicing and academic structural engineering community in California and engineers from Los Angeles Department of Building and Safety, listed in Table 1. They evaluated which types of buildings pose the greatest risk and approaches to fix the problems and drafted proposed ordinances for consideration by the City Council.

Table 1
The Mayor's Technical Task Force

Members	Affiliation	Members	Affiliation
Michael Cochran	President, Structural Engineers Association of California Associate Principal, Weidlinger Associates	Michael Mehrain	Principal/Vice President, URS Corporation Member, Los Angeles Tall Buildings Design Council
David Cocke	President, Structural Focus	Farzad Naeim	President, Farzad Naeim Inc. Member, Los Angeles Tall Buildings Design Council
Melvyn Green	President, Melvyn Green and Associates	Kevin O'Connell	President, Structural Engineers of Southern California Principal, Simpson Gumpertz & Heger
William T. Holmes	Senior Consultant, Rutherford +Chekene, Consultant to FEMA	Doug Thompson	Past President, Structural Engineers of Southern California Partner, STB Structural Engineers
Frank Bush Raymond Chan Victor Cuevas Catherine Gaba Ken Gill Ifa Kashefi Colin Kumabe	Los Angeles Department of Building and Safety	John Wallace	Professor, UCLA Department of Civil and Environmental Engineering

The technical issues for the water system were addressed by a team of Los Angeles Department of Water and Power employees who were subject matter experts in the various water system components, directed by Craig Davis. The telecommunication issues were considered by representatives of the four cellular providers. In addition to these three task forces, many outside experts were engaged to address particular issues.

Much of the year's work was meeting with stakeholders in Los Angeles's future, including elected and city department officials, building owners, business leaders, real estate managers, civic leaders, and community organizations, and enabling them to understand the consequences of possible recommendations and to compare the expected losses with the costs of mitigation. Over 130 meetings were held in the ten months from the beginning of February 2014 to the release of the report on 8 December 2014. Most of the meetings involved a presentation about the science about the seismic risk and economic consequences, a time for questions and discussion about the risk, a discussion about possible approaches to addressing the risk, and solicitation of ideas for new approaches. The primary focus in the stakeholder discussions was on the potential for economic disruption (Fig. 4).

> **Relationships matter. … People listen to people they trust, and that trust comes from familiarity and shared experience.**

The three tracks of recommendations for buildings, water, and telecommunications were developed in parallel to address overlap between the tracks and to keep the focus on economics. The argument for economic fragility is the strong interdependence of systems in a modern complex urban environment, so that, for instance, the loss of the water infrastructure had the potential to disrupt a large part of the economy, or that the loss of another person's buildings would reduce the value of yours through blight or cordoning off properties adjacent to a damaged building. Thus it makes no sense to spend a lot of money fixing buildings, if there will be no water to allow occupancy after the earthquake anyway.

The result of this process is a series of recommendations in a report published by the Mayor's office, *Resilience by Design* (Los Angeles, 2014), and listed in Table 2. Some of these recommendations are for executive action (e.g., 1d, or 2g), and implementation in the city departments has already begun. Other recommendations will require ordinances from the City Council (e.g., 1a and 1b) or funding through taxes or bonds (e.g., 2h). The Mayor has begun work with other elected officials to bring this about.

LESSONS LEARNED

The work with Los Angeles has been a closer collaboration with policy makers and elected officials than any previous experience in my career as a scientist. The result has been proposals for some of the biggest shifts in seismic policy ever seen in southern California. It is worth reflecting on the process and trying to understand what aspects of this project have led to its success.

One fundamental insight has been gaining clarity on the difference between science and policy even as policy makers and scientists worked in closer collaboration. As a scientist, I can give the policy makers a prediction of the probable consequences of their decisions. As a citizen and voter, I have an opinion as to the appropriate policy to respond to that information, but that is not part of the science. We elect our policy makers to choose the policy. This is important for two reasons. First, if the scientists start making policy, we invite the politicians to start making science. Second, the policy makers fight for the policies they have made, so empowering them with the information to make more informed decisions also creates more forceful advocates in the people who actually have the power to get something done.

Second, it was important as we brought the science to the decision makers to stay focused on what we know rather than on the uncertainties. As scientists, we know that uncertainties matter, and to convince our colleagues of our results, we need to demonstrate that we have analyzed and understand the uncertainties. Policy makers need the answers. They rely on hearing a consensus from the scientists to know that we have done our job. So results are most effective when you can demonstrate that the results are the consensus of the scientific community, and then you give the results and not the process by which the scientists achieved the results.

Third, everyone supports something they help to create, so engaging stakeholders in the discussion from the beginning is a condition for success. Much of the year was spent in meetings, talking about the science, but also listening for ideas. Many of the details of the recommendations came from people who will be affected by the plan and who could have become impossible barriers to its enactment. Being able to affect some piece of the plan gave them a stake in its success.

Fourth, relationships matter. The city of Los Angeles did not suddenly decide to listen to the scientists. This collaboration is the culmination of decades of interactions, especially the closer collaboration that developed out of the ShakeOut scenario process in the Multi Hazards Demonstration Project. For the last 7 yr, many scientists have been engaged in close collaboration with emergency managers, utility engineers, and regional officials. With the now annual ShakeOut drill, the message about earthquakes is being heard on a more regular basis, and it is connected to the credibility of scientific analysis. It is not just the credibility of the science (which has always been there) but also the relationship with the scientists. People listen to people they trust, and that trust comes from familiarity and shared experience.

ACKNOWLEDGMENTS

A large number of people contributed to the resilience project in Los Angeles, and they are listed in the report on the project at http://lamayor.org/earthquake (last accessed February

Table 2
Recommendations for Seismic Resilience from the Resilience by Design Report (Los Angeles, 2014)

1. Strengthen Our Buildings	2. Fortify Our Water System	3. Enhance Reliable Telecommunications
(a) Mandate retrofit of soft-first story buildings to make the first floor as strong as the second	(a) The Fire Department and Water Department will develop a resilient and alternative water system for fire-fighting purposes	(a) The city should enter into a Memorandum of Understanding with cellular service providers to maximize access to telecommunication coverage in a disaster
(b) Mandate that concrete buildings designed prior to the enactment of the 1976 Uniform Building Code meet the Basic Safety Objective (BSO) in the AFSCME 41	(b) Identify mitigation alternatives for the Los Angeles Aqueduct crossing the San Andreas fault by July 2015 and then implement	(b) Develop solar-powered citywide WiFi to provide a telecommunications alternative that uses less power and will allow Internet access in a time when the cell system is disrupted
(c) Mandate retrofitting of buildings that incur excessive damage in a low level of earthquake shaking (less than 40%*g* on the USGS ShakeMap)	(c) Create a Seismic Resilience Water Supply Task Force with the Department of Water and Power (DWP), California Metropolitan Water District, and the Department of Water Resources, in an effort to create a collaborative and regional approach to protecting the resilience of our water supply	(c) Create a Southern California Utility Resilience Task Force to develop solutions to the potential for cascading failures in the interacting utilities as they cross the San Andreas fault
(d) Adopt a "Back to Business Program" to supplement the capacity of the city's building inspection force in the event of a major earthquake	(d) Ensure that DWP dams are maintained in a safe and reliable manner to both ensure a reliable water supply and to ensure public safety in the event of an earthquake	(d) Amend the building code to require new freestanding cellular communication towers to be built with an Importance Factor of 1.5. Existing towers would not be affected
(e) Adopt and implement a voluntary rating system, utilizing the system designed by the United States Resiliency Council	(e) The 2010 Urban Water Management Plan to develop local water supplies through storm water capture, water conservation, and water recycling should be actively pursued	(e) The city of Los Angeles and the USGS will begin to implement early earthquake warning in southern California. The city of Los Angeles should work with Congressional Representatives to support a robust EEW system in California
	(f) Commit to a future water system with a seismically resilient pipe network	
	(g) Establish a Resilience by Design Program at the highest level of DWP, covering both the power and water systems to promote seismic resilience as a core function of DWP	
	(h) Work with local, regional, and state partners to develop a seismic resilience bond measure to allow investment in the seismic safety of our region	

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