Summer 2019

ENGINEERING FOR DISASTER RESILIENCE

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Editor's Note

Features

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News and Notes

Editor's Note

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The Rapidly Growing Need for Resilient Infrastructure

Planet Earth is both highly populated and increasingly unsettled with respect to natural hazards. Population expansion exposes large numbers of people and expanses of infrastructure to extreme events such as earthquakes, tsunamis, hurricanes, floods, and wildfires. These and other disasters can disrupt the social fabric and economic balance of an entire region, and even cascade into worldwide supply chain disruptions, insurance losses, and financial instability.

Within the past 15 years the world has witnessed the 2004 Sumatra-Andaman and 2011 Tōhoku earthquakes and tsunamis, the 2010 earthquake off the coast of Chile, and the 2010–11 Canterbury (NZ) earthquake sequence. Three of these earthquakes are among the largest six ever recorded. In the United States, Hurricanes Katrina (2005), Sandy (2012), Harvey (2017), Maria (2017), and Irma (2017) are the country's five most expensive hurricanes—three of them in the same year.

Instead of being rare events, megadisasters from natural hazards will be experienced with much greater frequency. The severity and far-ranging consequences of these events are establishing a new normal for natural disasters—and a corresponding challenge to the engineering profession to help develop the resilient infrastructure needed to reduce their impact.

Resilience can be defined as the ability of a community to withstand and recover rapidly from disruptions and to adapt to changing conditions (White House 2011). Infrastructure provides the resources and services that sustain communities. It includes public and private sector buildings, transportation facilities, energy generation and delivery systems, water supplies, telecommunications, and waste conveyance and treatment networks.

Resilient infrastructure, however, involves much more than the protection and emergency operation of core facilities. It involves complex interactions among the government agencies and utilities that operate it, the companies and businesses that design and build it, the institutions that finance and fund it, and the people who depend on the infrastructure (NIST 2016).

A prevailing theme among the articles in this issue is the social dimension of infrastructure and the corresponding need to approach resilience as both a social and technical problem. Infrastructure policy and progress must address the combined social and technical dimensions of infrastructure, including interdependencies among the physical, social, and economic systems that communities depend on.

An extra dividend from investment in resilient infrastructure is improved performance on a day-by-day basis. These investment returns are quite significant in the long term when improvements in safety and efficiency are integrated over many years. Daily improvements add to the value gained from the primary goal of avoiding infrastructure disruption and its economic impacts, which are substantial under extreme conditions.

Innovation to Enhance Resilience

If necessity is the mother of invention, then—in a world with an expanding population and simultaneous exposure to the effects of climate change—reducing the impact of natural hazards should necessitate innovation. Natural hazards have in fact been major agents of change in approaches to infrastructure, acting as a catalyst for improving performance under extreme conditions and for planning and engineering that improve daily operations.

The articles in this issue present examples of engineering innovation to develop resilient infrastructure. The innovations involve new ways of formulating and managing risk, of planning and constructing for multiple hazards, and of engaging communities and public/private agencies. Some of the most creative work on infrastructure involves engineering to reduce earthquake and hurricane risk.

One of the great challenges of developing infrastructure is the dual character of the task: Infrastructure is both local—embedded in the local population, inventory of buildings and facilities, business structure, and politics—and subject to universal principles of engineering and social behavior. The general principles of infrastructure must be addressed contemporaneously with the particular characteristics of local communities. Moreover, there is never only one approach, and local solutions are subject to change over time.

Resilient infrastructure provides valuable insight on how to deal with this dual character. The urgency of addressing hazards, especially in vulnerable communities, helps to promote common purpose and gain public support. At the same time, lessons learned in Los Angeles and San Francisco for infrastructure resilient to earthquakes and in New York City and Houston for infrastructure resilient to hurricanes have relevance for communities at risk everywhere: Experience gained from addressing one type of hazard has value for communities subject to other types of hazard. Organizational and financial innovations to reduce the risk of natural hazards provide clues for advancing infrastructure more generally.

In This Issue

The opening op-ed by New York's Governor Andrew Cuomo describes the rehabilitation of the Canarsie Tunnel, an example of infrastructure innovation following Hurricane Sandy. The tunnel is a critical link in a New York City subway line that carries 250,000 daily commuters, and its rehabilitation was required to repair structural and electric power components damaged by Hurricane Sandy. The project, which started nearly seven years after the hurricane, illustrates the long tail of the recovery curve for core infrastructure after a natural disaster. It also shows the importance of community-oriented objectives in the implementation of resilient infrastructure. In this instance, community objectives were met by breaking the rules of conventional tunnel rehabilitation and overturning traditional agency approaches by enlisting an external academic expert team empaneled by the governor to review the project plans.

Next, Bilal Ayyub and Alice Hill address climate change and its effects on resilient infrastructure design. They discuss approaches for dealing with uncertainty and show how the engineering community is responding to climate change with risk-based adaptive design procedures. They provide guiding criteria, questions, and examples, and review policy options for building resilient infrastructure.

Charlie Scawthorn and Keith Porter provide further treatment of risk-based engineering with a discussion of performance-based design (PBD) and its adaptation to multiple hazards. They report on the benefits of improved building codes for resilient infrastructure, and illustrate with an example of benefits from resilient water distribution grids to reduce fire risk in cities vulnerable to earthquakes. They consider technological, institutional, and regulatory issues that need to be addressed for an effective multihazard approach.

Greg Baecher, Michelle Bensi, Allison Reilly, Brian Phillips, Ed Link, Sandra Knight, and **Gerry Galloway** explore the paradigm shift from standards-based engineering approaches to risk-informed project plans for resilient infrastructure. They focus on the impact of hurricanes and floods on the evolution of infrastructure design, and consider the implications of a shift from 20th to 21st century hazard-resilient practices for the education of the next generation of engineers.

In the next article, Chris Rojahn, Laurie Johnson, Veronica Cedillos, Terri McAllister, Steve McCabe, and I discuss societal needs and the interdependencies of six critical infrastructure systems: electric power, gas and liquid fuel, water, wastewater, telecommunications, and transportation networks. Based on an assessment of lifeline infrastructure performance commissioned by the National Institute of Standards and Technology (NIST), suggestions are provided for policy, modeling, and research, as well as infrastructure performance levels and timeframes for recovery of critical services and resources.

Bruce Ellingwood, John van de Lindt, and Terri McAllister address the development of resilient communities and describe the work of the NIST-supported Center for Risk-Based Community Resilience. The efforts of this multiuniversity consortium go beyond improvements in physical assets and emergency response to consider the social needs of communities, including postdisaster recovery.

Lucy Jones and Marissa Aho explain how the City of Los Angeles has addressed natural hazard risk by implementing a long-term plan, *Resilience by Design*, to improve seismic resilience through city council ordinances, executive action, and partnership activities. They discuss how science and policy are integrated in the city plan, and draw useful lessons from the Los

Angeles experience for other scientists, engineers, urban planners, and communities that want to connect scientific research to policies for resilient communities.

Craig Davis and John Shamma describe a historic collaboration of the Los Angeles Department of Water and Power, Metropolitan Water District, and California Department of Water Resources to develop and apply measures for a seismic-resilient water supply for the 19 million residents of the Los Angeles–San Diego region. They focus on projects to ensure flowing water in the event of a significant rupture of the San Andreas Fault and a collaborative plan for systemwide risk reduction. The formation of this regional task force required overcoming institutional constraints and differences in organizational culture to achieve unity of purpose and commitment to widespread improvements.

The Way Ahead

A critical overarching factor in these articles is the institutional culture of the agencies and organizations responsible for planning, constructing, and maintaining infrastructure. That culture is at the heart of future changes in the way engineers do business. Necessary changes in approach start with the recognition that there is an important difference between *change agents* and *agencies that don't change*.

As engineers, we need to ask ourselves if we want to be participants in agencies that change versus those that do not. For infrastructure this is an existential question. The infrastructure challenges facing the nation are so large that progress will be achieved only through changes in the culture of operating and regulatory agencies, reductions in institutional restrictions, and innovations in financing and funding to create resilient and sustainable systems.

The development of resilient infrastructure provides many lessons and fresh thinking about the changes needed to accommodate extreme demands amid complex technical and social conditions. I hope this issue will stimulate fresh thinking about infrastructure and be a change agent for much-needed improvements.

Acknowledgments

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Op-ed

Post-Sandy Engineering Innovation in New York City

Andrew Cuomo is governor of New York.

New York is what it is because we built it that way. The Erie Canal, the Brooklyn Bridge, the Empire State Building, the Holland Tunnel—these engineering marvels exemplify the bold spirit that characterized New York for decades. And the New York subway system was no different. Opened in 1904, its 600 miles of tunnels revolutionized the way people lived, traveled, and did business in the greatest big city on Earth.

Yet as decades passed and president after president paid lip service to rebuilding the nation's crumbling infrastructure, the United States fell behind. Today, other countries are developing faster than ever before, using emerging technologies that challenge and rethink conventional approaches to engineering. Their unique approaches and out-of-the-box thinking have produced marvels of their own—the Burj Khalifa in Dubai, the Millau Bridge in France, the Gotthard Tunnel from Switzerland to Italy.

In New York, our subway system for too long fell victim to the same neglect that has plagued infrastructure across the country. The Metropolitan Transportation Authority (MTA), created in the 1960s as a sort of holding company for the region's subway, commuter rails, and the Triborough Bridge and Tunnel Authority, grew into a bloated bureaucracy that lacked accountability or the innovative spirit that had built the subway system in the first place. Major capital projects were consistently delayed for years or decades, and the MTA relied on the same technologies, approaches, and vendors that it always used.

No project better exemplified the MTA's stale approach to the region's transit infrastructure than the effort to rehabilitate the Canarsie Tunnel between Brooklyn and Manhattan. The century-old tunnel that carries the New York City subway L train under the East River was severely damaged by saltwater from Hurricane Sandy in 2012 and was in dire need of repair.

But confronted with a unique opportunity to employ innovative tools and technologies to strengthen the tunnel for the next century, the MTA instead decided to rebuild the tunnel the same way it had been built nearly 100 years before.

The original rehabilitation plan called for the entire removal and replacement of the tunnel bench wall, the concrete structure that houses the power and signal cables along the tunnel. It was to be a painfully long project and would have required completely shutting down the tunnel for 15 months, affecting roughly 250,000 daily commuters. While New York City and the MTA were diligent in their efforts to provide alternative service to alleviate the nightmare scenario for commuters caused by the L train shutdown, I wanted a second opinion.

In December 2018, before the scheduled shutdown, I charged a panel of engineering experts, including the deans of the engineering schools at Cornell and Columbia Universities, to closely review the plans to rehabilitate the L train tunnel. I asked them to view the project through a different lens and consider modern, innovative approaches. After spending hundreds of pro bono hours reviewing the original plan with the design engineers and discussing possible alternatives, the team designed a new approach that uses emerging yet proven technology that enhances the tunnel's resiliency and safety and has far less of an impact on riders.

Instead of removing and replacing the entire bench wall, the team recommended that the MTA use a cable racking system widely used in modern train tunnels, including the London Underground and Riyadh Metro. These racks offer easier access for maintenance and cable upgrades, among other benefits. Additionally, instead of replacing the entire bench wall, the plan calls for removal of only the heavily damaged sections, leaving the structurally sound parts intact. And it reduces the amount of hazardous silica dust that would have resulted from complete demolition of the bench wall.

The damaged portions of the bench wall will be fortified with fiber-reinforced polymer, a proven technology commonly used to strengthen bridges. Moreover, a high-tech fiber optic system will be used to monitor the structural integrity of the bench wall and the tunnel itself, providing real-time data that will enable the MTA and contractors to make any necessary repairs for years to come.

Not only does this innovative plan improve the structural integrity of the tunnel, but it will avert a full shutdown of the L train by limiting work to nights and weekends.

When approaching large-scale infrastructure projects that impact millions of people, it is important to include fresh perspectives and ideas that challenge conventional approaches. The L train rehabilitation project combined unique perspectives and varied engineering expertise to produce a safer, more efficient plan.

The lessons learned from the L train project can be applied to other major infrastructure projects, and New York is doing exactly that. This year, we passed a law requiring that major capital projects—including the East Side Access project connecting the Long Island Rail Road to Grand Central Terminal, which for decades has been the poster child for MTA mismanagement—undergo a full review by an outside expert panel so we can apply innovation and creativity to how we build.

While the federal government continues to fail at addressing our nation's crumbling infrastructure, New York is again leading the way in building for the future and serving as an example for the rest of the nation to follow. I hope other states will follow New York's lead, and use bold, innovative approaches to address one of the greatest challenges of our time.

Engineers and policymakers must embrace planning and design practices and policies that ensure climate-resilient infrastructure.

Climate-Resilient Infrastructure: Engineering and Policy Perspectives

Bilal M. Ayyub and Alice C. Hill

Bilal M. Ayyub

Alice C. Hill

Each year, governments and the private sector invest trillions of dollars in infrastructure that may not withstand future risks from climate change (Oxford Economics 2017). Most of the world's new infrastructure will be built in developing countries, which face the dual challenges of disaster response and urbanization (Oxford Economics 2017), but responding to natural disasters is also a major challenge in developed countries. Damage from Hurricanes Harvey, Maria, and Irma totaled approximately $265 billion, making 2017 the most expensive hurricane season in US history (Drye 2017; Heathcote 2017; NOAA 2018). Long-lived infrastructure must be resilient to weather extremes, the effects of climate change, and other hazards.

Background

Infrastructure development requires a broad range of actors, including policymakers, planners, funders, engineers, researchers, and communities. Together they shape the physical structures and services intended to provide critical support to the public for decades. Some of these actors have attempted to integrate consideration of future climate risk into infrastructure decisions. For example, the American Society of Civil Engineers (ASCE) developed a top-down approach for adaptive risk management that starts with the climate

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scenario and projections shown in figure 1. But despite these promising efforts, innovative ideas and strategies for addressing climate risks are not yet common practice.

How can resilience be designed, funded, and incorporated in public infrastructure investments? This question puts engineers and other professionals in a race against a changing climate to enhance planning and design practices.

Climate and weather are exhibiting intensifying extremes, but infrastructure systems traditionally have been designed, constructed, operated, and maintained according to assumed stationary climate and weather conditions in stochastic terms, without taking account of future climate change and associated uncertainties that increase and intensify hazards. Adaptation technologies, adaptive designs, and appropriate new policies (e.g., addressing risk management) are necessary to reduce climate impacts and risks.

A Changing Climate and National Impacts

In 2014 the Intergovernmental Panel on Climate Change (IPCC) concluded that warming of the climate system is unequivocal and that it is extremely likely that the dominant cause of the observed warming since the mid-20th century is human influence. Graphs from the congressionally mandated Fourth National Climate Assessment (NCA4; USGCRP 2018) depict these trends in figures 2 and 3. Since the 1950s, anthropogenic greenhouse gas (GHG) emissions have driven many of the observed changes, which are unprecedented over decades and even millennia (IPCC 2014). Future GHG emissions are uncertain and depend on many fac-

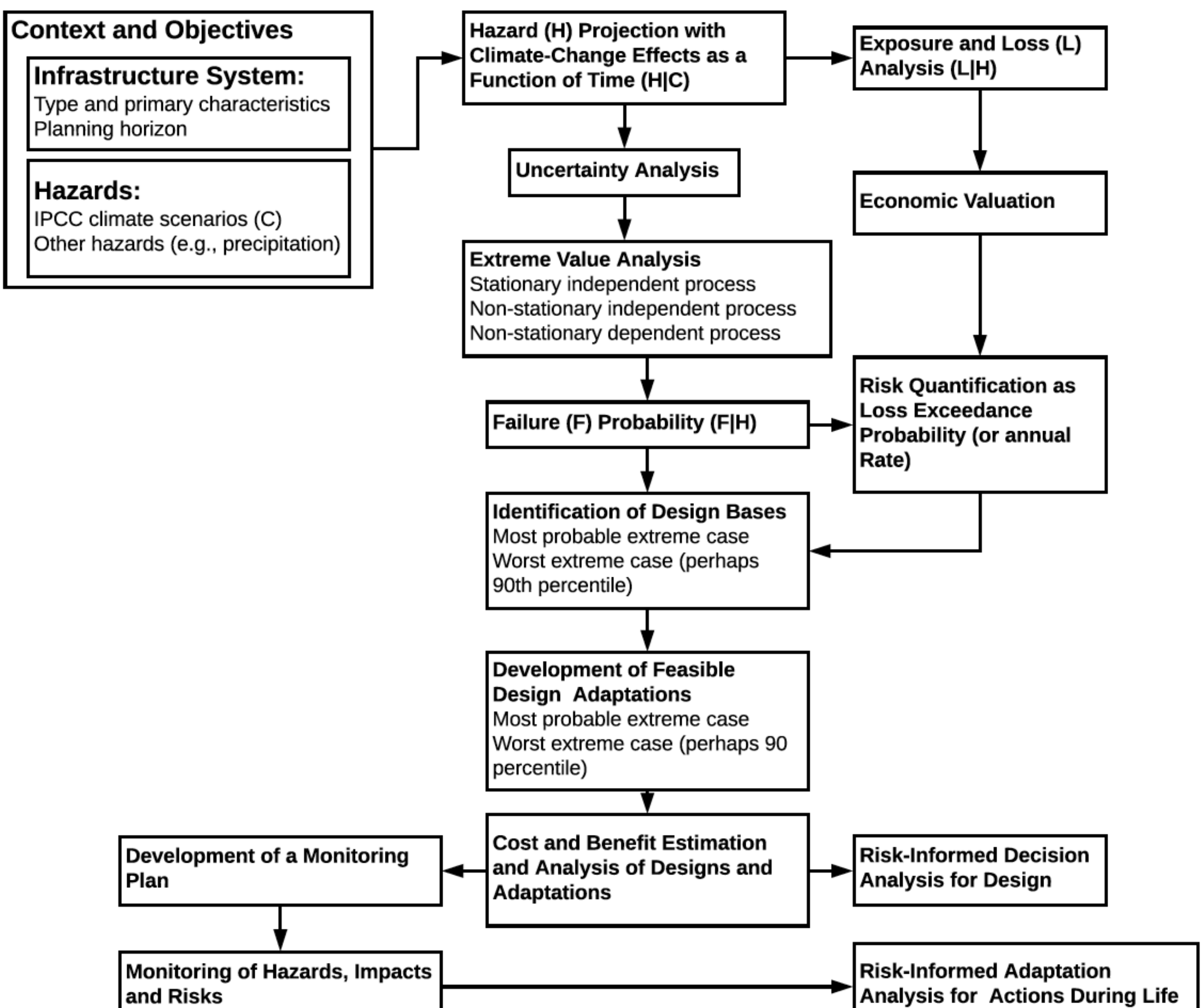

FIGURE 1 Risk-based adaptive design (ASCE 2018, adapted from Stewart and Deng 2015).

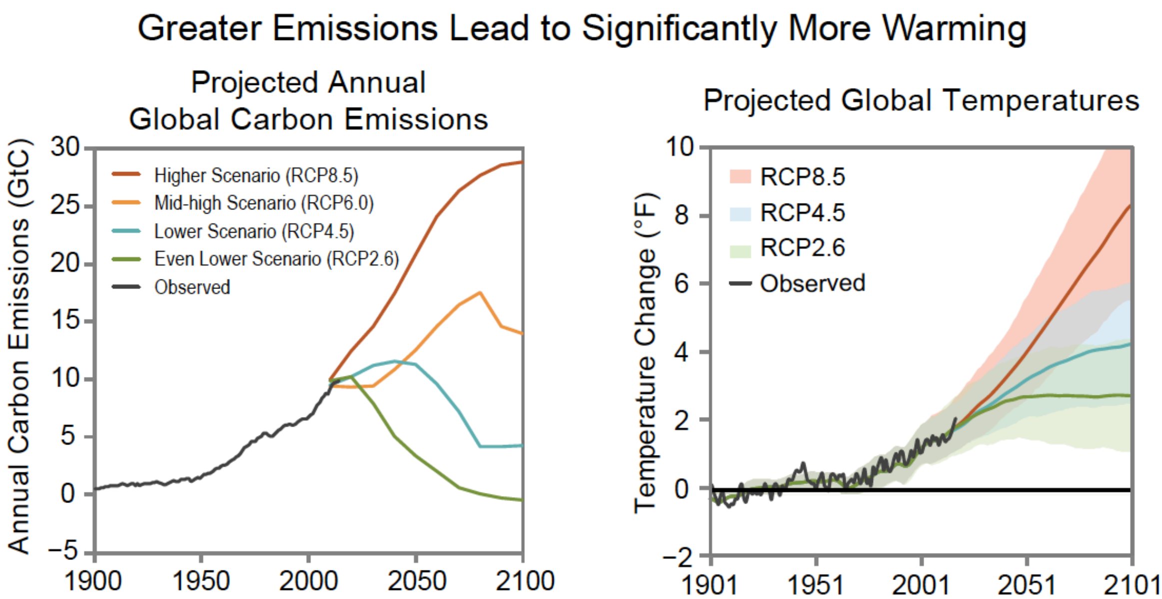

FIGURE 2 *Left:* Annual historical and plausible future carbon emissions (measured in gigatons of carbon, GtC per year). *Right:* Observed and projected temperature change for a range of future scenarios relative to the 1901–60 average, based on central estimates (lines) and ranges (shaded areas, two standard deviations) simulated by the full suite of CMIP5 (Coupled Model Intercomparison Project Phase 5) global climate models. By 2081–2101, the projected range in global mean temperature change is 1.1°–4.3°F under the lowest scenario shown (RCP2.6; 0.6°–2.4°C, green), 2.4°–5.9°F under the lower scenario (RCP4.5; 1.3°–3.3°C, blue), 3.0°–6.8°F under the mid-high scenario (RCP6.0; 1.6°–3.8°C, not shown), and 5.0°–10.2°F under the highest scenario (RCP8.5; 2.8°–5.7°C, orange). The Representative Concentration Pathway (RCP) is a greenhouse gas concentration trajectory adopted by the IPCC. Source: USGCRP (2018).

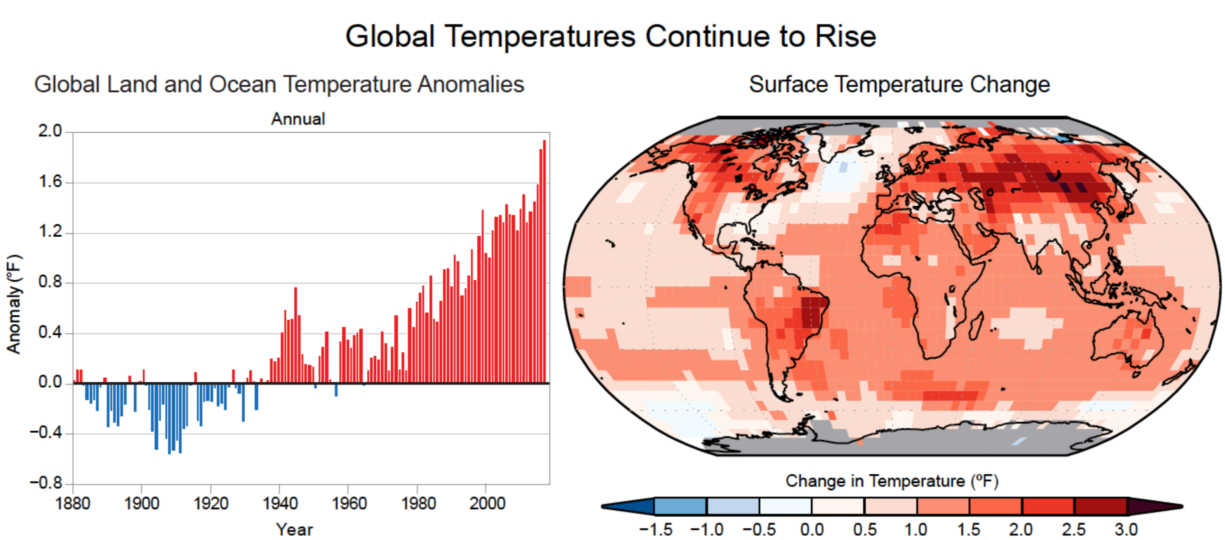

FIGURE 3 *Left:* Global annual average temperature has increased by more than 1.2°F (0.7°C) for the period 1986–2016 relative to 1901–60. Red bars show temperatures above the 1901–60 average, blue bars indicate temperatures below the average. *Right:* Surface temperature change (in °F) for the period 1986–2016 relative to 1901–60 (grey indicates missing data). Source: USGCRP (2018).

tors, including policy, population growth, globalization, economic activity, and human behavior, all of which require the use of projections to define emissions pathways (European Commission 2015; Hausfather 2018).

According to the NCA4, the global annually averaged surface air temperature increased by about 1.8°F (1.0°C) from 1901 to 2016. This 115-year period is now the warmest in the history of modern civilization, and the last few years have also seen record-breaking climate-related weather extremes. Researchers have documented changes in surface, atmospheric, and oceanic temperatures; melting glaciers; diminishing snow cover; shrinking sea ice; rising sea levels; ocean acidification; and increasing atmospheric water vapor.

Without major emission reductions from policy, behavioral, or technological change, annual average global temperature relative to preindustrial times could increase by 9°F (5°C) or more by 2100. With significant reductions, it could be limited to 3.6°F (2°C) or less, which would still be associated with serious climate impacts.

In light of the uncertainties surrounding how much climate will change, climate scientists and engineers struggle to accurately characterize future climate and weather extremes even in probabilistic terms, requiring projections based on numerous assumptions about GHG pathways.

Improving Engineering Design for a Changing Climate

While the evidence that climate is changing is very strong, the engineering community has found it difficult to incorporate consideration of climate change at temporal and spatial scales relevant to engineering practice. Development of adaptation and mitigation technologies and strategies has proved elusive based on current practices.

As an example, relative sea level rise (SLR) is a locally observable phenomenon that reflects changes in the eustatic sea level, the subsidence or uplift of the sea floor, and the accumulation, erosion, or compaction of sediment along the coast. Sediment accumulation and erosion are greatly affected by subsidence and uplift, so these processes are often mutually reinforcing (ASCE 2018). The tectonic setting of continental margins plays a primary role in determining whether a section of coastline experiences uplift or subsidence due to large landmasses breaking up with geological interactions. In addition, glacial loading contributes through (a) glaciation depression, with associated isostatic adjustments during periods of widespread continental glacial coverage, or (b) rebounding due to glacial retreat, creating uplift at rates slower than that of the retreat. Besides long-term changes on geologic time scales, relative SLR is affected by fluid withdrawal, diversion or elimination of sediment sources, and other human activities.

High-resolution SLR projections are important for the development of durable engineering designs. They are useful tools to support coastal hazard mitigation design criteria and communicate projected changes to stakeholders. However, engineering works must also consider the significant unknowns in future SLR, including those resulting from possible GHG pathways and those based on the behavior of ice sheets, which remain uncertain.

Dealing with Uncertainty in Engineering Design: Observational Method

Civil engineers have dealt with uncertainty in geotechnical engineering practice by employing the observational method (OM), originally proposed by Karl Terzaghi (Nicholson et al. 1999; Peck 1969; Terzaghi and Peck 1948). The specific steps in a climate change OM (modified after Terzaghi and Peck 1948) are as follows (also see Ayyub and Wright 2016):

1. Project design is based on the most probable weather or climate condition(s) rather than the most unfavorable. The most credible unfavorable deviations from the most probable conditions are identified.
2. A course of action or design modification is devised (in advance) for every foreseeable unfavorable weather or climate deviation from the most probable condition(s).
3. The performance of the project is observed over time (using preselected quantities) and the response of the project to observed changes is assessed.
4. Design and construction modifications (previously identified) can be implemented in response to observed changes.

Figure 4 provides an example and ASCE (2018) includes additional examples.

Uncertainties and Design Philosophies

The uncertainty associated with future climate is not completely quantifiable, and therefore accounting for it in engineering practice requires understanding and treatment of uncertainty as well as engineering judgment. Uncertainty can be broadly classified as follows for convenience (Ayyub and Klir 2006):

1. recognized and well characterized (e.g., materials properties);
2. recognized but moderately characterized (e.g., future precipitation, hurricanes, wind speed);
3. recognized but poorly characterized (e.g., future energy use by populations worldwide);

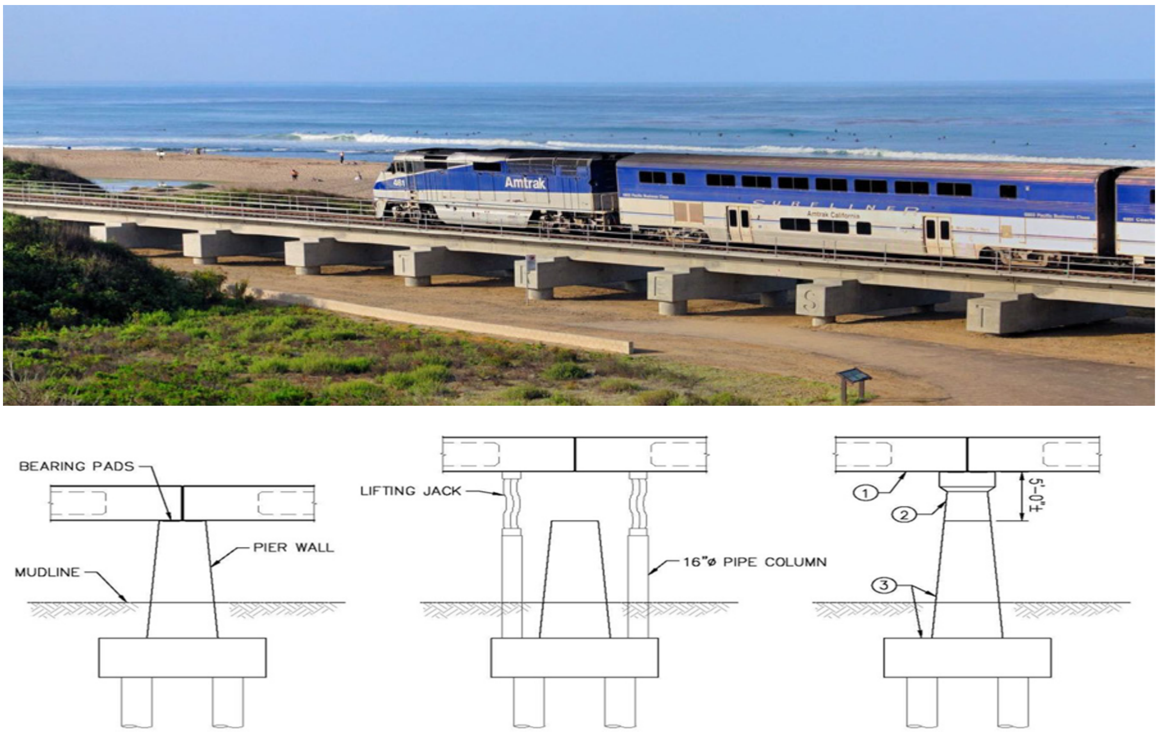

FIGURE 4 Use of the observational method for climate-resilient infrastructure. (a) Los Angeles to San Diego (LOSSAN) rail corridor that follows the California coast and crosses low-lying areas on trestles. (b) LOSSAN rail corridor using precast piers and caps to allow insertion of additional pier segments if needed to adapt to flooding hazard. Adapted from Dial et al. (2014) and ASCE (2018).

4. recognized but not characterizable (e.g., global governance and cooperation); and
5. of unknown existence or nature (e.g., physical laws or behaviors not yet discovered or undiscoverable based on current methods and research pursuits).

Climate projections entail similar types of uncertainty (Stainforth et al. 2007), although they are expressed differently for the purpose of communication to the public; however, these five classes offer a basis for engineering and planning guides and standards.

It is common practice in engineering to classify uncertainties as (a) aleatory and (b) epistemic. The former is considered inherent to the situation and irreducible with data collection, although its characterization can be enhanced. The latter is reducible with data collection or investigation, although the economic cost of investigating the data might not justify the reduction.

Planning for a changing climate entails planning not only for climatic uncertainty but also for uncertainty about regulatory, environmental, economic, social, and other conditions affecting an engineering project.

Risk Assessment

Risk methods provide practical means for managing uncertainty (Ayyub 2014). Risk is commonly measured in simple terms as the probability of occurrence of an event or scenario and the outcomes or consequences associated with the occurrence. Risk assessment is primarily concerned with answering three questions (Kaplan and Garrick 1981):

1. What could happen?
2. How likely is it to happen?
3. If it does happen, what are the consequences?

Risk assessment is thus a systematic process to identify potential, uncertain events, including hazards, to estimate occurrence likelihood and determine the consequences of events.

Engineers should develop a new paradigm for engineering practice as climate change, population growth, and development patterns alter the risk profiles of projects, communities, and even nations. The effects of climate change may be difficult to estimate with a high degree of certainty in many instances, but clear indications are available of some effects, such as SLR, more frequent extreme heat events, and an increase in the number of extreme events in areas where they have rarely been encountered. These suggest a changing footprint of risk, regardless of the magnitudes of the events on regional or national scales.

Accounting for Uncertainty in Engineering Design

Engineers design infrastructure by accounting for uncertainties to achieve acceptable safety levels and appropriate physical and economic efficiencies. Uncertainty is thus foundational in developing a design philosophy. Engineering design evolves based on an enhanced understanding of uncertainty.

The five types of uncertainty noted above drive engineers toward practice enhancements. When uncertainty is recognized and well characterized, engineers use traditional factors of safety, followed by reliability-based design in building codes. For cases 2 and 3, where uncertainty is recognized but moderately or poorly characterized, engineers use reliability-based or risk-informed designs.

When dealing with climate change, it is important to recognize that it is not possible to define a hazard with probability distributions a priori. Scenario modeling, which can be used to perform sensitivity analysis and address variability, incorporates conditional probabilistic information such as uncertainties owing to spatial variability of seismic demand, random phasing of ground motion, local soil conditions, and performance levels of civil infrastructure (which can be gauged from fragility curves as conditional probabilities for varied hazard levels). Scenario modeling is helpful to design for a changing climate, but may be insufficient.

Robust Decision Making

Robust decision making (RDM) can address cases where deep uncertainty is recognized but either poorly characterized or incapable of being characterized. It provides an analytic framework to identify strategies that can perform over a wide range of poorly characterized uncertainties. In turn, RDM strategies may provide a basis for a number of scenarios to be analyzed while incorporating probabilistic information.

The RDM framework could identify strategies that would be insensitive to vulnerabilities associated with deep uncertainty in future climate projection models. However, it might not produce cost-effective solutions.

Adaptive Risk Management

When uncertainty is unrecognizable or it is not possible to fully define and estimate the risks and potential costs for a project to reduce the uncertainty in the timeframe in which action should be taken, engineers should use adaptive design or risk management. These are most effective in cases 4 and 5, although they can be used in others. Wilby and Dessai (2010) present a robust framework called *adaptive management* of climate risks, which involves monitoring of the environment and systematic assessment of the performance of measures installed. The approach calls for inventorying preferred adaptation strategies that are then synthesized into a subset of measures that reduce vulnerability under the current climate regime. The resulting strategies should be able to perform well over a variety of scenarios, regardless of climate change and conditions.

Scenario modeling is helpful to design for a changing climate, but may be insufficient.

The OM, a technique of adaptive risk management, offers the means to enhance projects' resiliency to future climate and weather extremes. Rather than design approaches at a particular site based on probabilities of extreme events, engineers should seek alternatives that will do well across a variety of possible conditions, including those not yet identified. Such an approach enables the development of cost-effective strategies for making a project more resilient to future climate and weather extremes by including some initial level of enhanced resilience or adaptation rather than retrofitting later.

Seismic engineering research uses performance-based design, meaning a system is designed to operate at a set level of performance typically prescribed in standards. The design focuses on ensuring the functionality, durability, and safety of systems at appropriate mean recurrence intervals.

Adaptive risk management extends the concept of performance-based design to account for projected increasing risks from climate change impacts. As the characterization of hazards improves, for example with updated sea level projections, climate risks will be reexamined and managed for a project using built-in features that act as enablers to system changes in cost-effective terms.

Policy Options for Building Resilient Infrastructure

It is not just engineers who struggle with how to make sound decisions in the face of climate and other uncertainties. It is also policy- and decision makers in both the government and the private sector. There are at least three ways to ensure that policies guiding infrastructure keep pace with the escalating risks from climate change: planning for future risk, thinking systemically, and mainstreaming green infrastructure.

Planning for Future Risk

To mitigate future risks from a changing climate, it is necessary to start planning for them. Two ways to advance planning practices are to screen projects for climate resilience and/or require that they comply with resilient building standards and practices. Congress could require that, before any federal funds are invested in an infrastructure project, the project be screened by the funding agency to determine its resilience to climate impacts reasonably expected over the life of the project, including those that may affect operation and maintenance. If the screening reveals that the project will not withstand anticipated risks, the federal government should require alterations in design to ensure resilience or deny funding.

Adaptive risk management uses built-in features that enable system changes in cost-effective terms.

Similarly, restricting funding for development in areas at known risk for climate impacts—as Executive Order 11988, signed by President Carter in 1977, does for investments in floodplains—could increase resiliency.[1]

To ensure that infrastructure design and construction adequately account for future climate conditions, the federal government could also require that certain standards be met. The Federal Flood Risk Management Standard (FFRMS), established by President Obama (White House 2015) but rescinded by President Trump, is instructive. The directive required that when federal monies funded construction or substantial renovation of a structure in or near a floodplain, the structure had to be elevated 2–3 feet (or to a level consistent with the latest climate science).

To encourage federal investment in infrastructure that can withstand future climate extremes, the government could provide incentives for the incorporation of flexible design elements, as in the LOSSAN rail corridor (figure 4). If the project's design adequately accounts for future impacts, additional federal funds could be provided to cover the potential added cost of building resiliently, by, for example, expanding the size of culverts to handle increased precipitation projected in the foreseeable future.

Thinking Systemically

Thinking systemically about how to build infrastructure that is resilient to multiple sources of risk can help government policy reduce risks from climate change. For example, after Tropical Storm Allison in 2001, the Texas Medical Center (TMC), which lost 25 years of research data, took drastic steps to reduce future risks from storms to its multiacre campus. Among other measures, TMC relocated electrical equipment, lab animals, and experiments to higher floors. Elevating sensitive components of the hospital's work also reduced the threat of other risks, such as unauthorized tampering and theft.

Incorporating systemic thinking in policy can help ensure that infrastructure is resilient to many types of hazards. After a disaster, the government could require certain types of improvements so that structures are "built back better" as a condition of recovery funds used for rebuilding.

Mainstreaming Green Infrastructure

Mainstreaming green infrastructure in policy can help avoid costly grey infrastructure projects and may offer as much benefit as the latter.

When Hurricane Sandy struck the East Coast in 2012, it overwhelmed many infrastructure services, including flood defenses, which proved inadequate to handle the storm surge in several cases. However, coastal wetlands across the northeastern states prevented an estimated $625 million in additional flood damages during the

[1] https://www.fema.gov/executive-order-11988-floodplain-management

hurricane (Narayan et al. 2016). Areas with wetlands saw on average 10 percent—and in some cases as much as 29 percent—less property damage.

Thus ecosystems can provide valuable risk reduction services that perform as well as or better than infrastructure built by humans. Policy should take this into account and capitalize on the benefits of green infrastructure.

Conclusion

Coordination between policy and engineering practice is necessary to achieve cost-effective solutions such as climate-resilient infrastructure. Such coordination will depend on changes in the current practices of policymakers, planners, and designers.

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Performance-based design and risk-based pricing consider natural disasters and recovery over time, explicitly accounting for resilience.

Enhancing Resilience through Risk-Based Design and Benefit-Cost Analysis

Charles Scawthorn and Keith Porter

Charles Scawthorn

Keith Porter

Urban economies depend on shared infrastructure for water, power, communications, and transportation. This critical infrastructure can be impaired by design and construction flaws, deterioration over time, obsolescence, accidents, and excess demand, but this article focuses on damage from natural hazards, which may include earthquakes, tsunamis, volcanic eruptions, tropical cyclones, floods, ice storms, and fire. There is evidence that climate change will exacerbate losses due to hydrometeorological phenomena, primarily tropical cyclones, winter storms, and flooding but also wildfire (USGCRP 2018). To enhance infrastructure resilience to such hazards, we present a risk-based approach, called *performance-based design*, and make the case for considering the benefit-cost ratio and pricing risk in strategies and decisions.

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Recent Catalyzing Events

The 2011 Tōhoku Earthquake and Tsunami

Among the most egregious of recent infrastructure-hazard interactions was the 2011 Tōhoku earthquake and tsunami, which killed 16,000 people (National Police Agency of Japan 2019) and destroyed one of the world's largest nuclear power stations, bringing about the loss of 30 percent of electric power production in the world's third largest economy. Only 9 of the country's 54 nuclear units remain operational (Nippon.com 2018).

The total economic impact of the event is difficult to assess. Direct damage estimates are about $360 billion (in 2011 USD) but do not include widespread economic impacts from loss of agricultural production, business interruption, increased costs of fossil fuel power production to replace lost nuclear capacity, ongoing costs of the Fukushima cleanup, and nonmonetary environmental and psychosocial impacts (e.g., Shigemura et al. 2012; Steinhauser et al. 2014). The cleanup costs alone are estimated to be about ¥70 trillion ($626 billion) over the next 40 years (JCER 2017). Combined with the direct damage estimates, this is the first trillion-dollar natural disaster in history.

Moreover, ten years earlier, research had shown that a similar-sized event in 869 AD had caused tsunami inundation at least 4 km inland (Minoura et al. 2001). And a 2007 study estimated the 99 percent likelihood of a tsunamigenic earthquake magnitude of 8+ within 30 years (Satake et al. 2007).

Finally, it is worth noting that the owner of the Fukushima Nuclear Power Station, Tokyo Electric Power Company (TEPCO), had been forced in 2007 to shut its Kashiwazaki-Kariwa Nuclear Power Station (the world's largest) after the Niigata-Chuetsu-Oki earthquake, and has avoided bankruptcy since the 2011 disaster only because of massive subsidies by the Japanese government (McCurry 2012).

US Hurricanes and Wildfires

In 2005 Hurricane Katrina caused at least 1,200 deaths, $125 billion in damage, and the partial abandonment of New Orleans for several years—even though the event was clearly foreseeable and was due to a "cocktail of natural and human factors" (Bourne 2004). These included decades-long land subsidence and loss of protective marshes and barrier islands, and the failure of flood prevention infrastructure during the event.

Hurricane Sandy (2012) affected 24 states, with particularly severe damage in New York City due to storm surge, which flooded streets, tunnels, and subway lines and cut power in and around the city. US damages amounted to $65 billion. Hurricane Harvey in 2017 matched Katrina as the costliest hurricane on record, with $125 billion in damage (NHC 2018), primarily due to flooding in Houston and Southeast Texas. Hurricane Maria, also in 2017, caused over 3,000 deaths and devastated Puerto Rico, where recovery has been extremely slow. The economic damage from Katrina, Sandy, Harvey, and Maria totaled $450 billion (NHC 2018).

The trillion-dollar impacts of the 2011 Tōhoku earthquake and tsunami were predictable and could have been substantially mitigated.

Catastrophic wildfires in the western states have also been devastating, especially in California, which in 2017–2018 sustained 138 deaths and the destruction of over 31,000 structures (CalFire 2019), with economic losses approaching $30 billion (III 2019). Of interest is the strong correlation between extreme wind conditions and electric power line–caused ignitions, which have led to a number of catastrophic wildfires (Miller et al. 2017; Mitchell 2013; Syphard and Keeley 2015).[1] As a direct result of these wildfires, the largest investor-owned utility in the United States, Pacific Gas & Electric (PG&E), filed for bankruptcy (Bloomberg 2019). PG&E's debtholders and people harmed by the wildfires incurred an unrecoverable loss because of a risk that PG&E failed to adequately fund and instead externalized on them.

Using Performance-Based Design for Multihazard Resilience

To reduce, and in some cases prevent, such catastrophic losses—that is, to contribute to social and

[1] Analyses often show that electric-related ignitions account for only a small fraction of wildland fires (e.g., Prestemon et al. 2013), but this is misleading as most wildland fires are small and quickly suppressed. Strong winds are a common cause of overhead electric line arcing (and ignition) with rapid fire spread, resulting in very large wildfires that are difficult to suppress. Thus, electric-related ignitions account for a large fraction of major wildfires and associated losses (see Kousky et al. 2013).

economic resilience—the design of critical infrastructure needs to be responsive to the attendant risks. A risk-based approach called *performance-based design* (PBD) has emerged in the building design sector over the last several decades, first in fire protection design (Hadjisophocleous et al. 1998; Meacham 1998) and latterly in designs for earthquakes (FEMA 2012; Porter 2003) and wind (Larsen et al. 2016).

Performance-Based vs. Prescriptive Design

PBD has the potential to allow designers to tailor a new facility to achieve selected levels of risk. Expressed in meaningful terms for nonengineering stakeholders, risks to be managed include probabilistic repair costs, life-safety impacts, and loss of function—"the three Ds": dollars, deaths, and downtime.

Performance-based design offers the opportunity to balance up-front cost against long-term resilience in explicit calculations.

But in practice PBD is rarely used that way. Rather, it is most often used as a form of value engineering (VE)—to reduce the cost of construction while achieving the same degree of life safety that a more conventional, prescriptive design would achieve. That is, one could use PBD to create a better-performing building than prescriptive design would require at the same cost. Instead, PBD has often been used to cut corners—to provide the level of safety that prescriptive design aims for, but at lower cost, by reducing features that would be required under prescriptive design. PBD is mostly being used to save developers and owners money on the up-front construction cost, not to save more occupants' lives, or reduce future earthquake repair costs, or reduce the downtime that future tenants will suffer.

PBD thus offers greater potential to design for resilience. Like prescriptive design, it recognizes that it may not be possible to avoid extreme loads, but unlike prescriptive design it offers the opportunity via explicit calculation to balance up-front cost against long-term resilience. One can decide how to limit damage under extreme loads so that losses are acceptable and recovery is quick.

PBD has so far been applied largely to building design, although its potential application to other infrastructure has been recognized for some time (Chang 2009). We present a case study of performance-based design of a water supply system subject to earthquake excitation.

Use of PBD for a Water Supply System

We focus on how much of a water supply system to harden against earthquake damage. PBD in general and the Federal Emergency Management Agency guideline P-58 (FEMA 2012) in particular lack built-in norms so that, working on behalf of all or any facility stakeholders, the designer is free to make trade-offs between costs and future performance that seem appropriate.

In the application described here, we design a resilient grid of buried water supply pipes to satisfy standard objectives of benefit-cost analysis for a case with neither fixed input nor fixed output.

- Benefits are measured in terms of the reduction in the present value of future monetary and life-safety losses.
- Costs are measured in terms of the monetary cost to add earthquake-resistant pipe to the system to enhance its capacity to supply water after earthquakes.
- Life safety is valued monetarily using the US Department of Transportation's value of a statistical life (VSL), essentially the department's acceptable cost to avoid deaths and nonfatal injuries to unknown people at an unknown future time (sometimes called statistical deaths and injuries) (USDOT 2015).

In a situation without fixed costs or benefits, the optimal design is the largest investment that produces an incremental benefit that exceeds the incremental cost (see, for example, Newnan et al. 2004 for the basics of such a benefit-cost analysis).

Designing a Resilient Water Supply Grid

A study by the National Institute of Building Sciences examined the benefit-cost ratio (BCR) of meeting or exceeding current building codes. It found that model building codes save society $11 per additional $1 spent relative to code requirements of 30 years ago (MMC 2018, referred to as Mitigation Saves 2, or MSv2). It also found that design to exceed current code requirements could save society $4 per additional $1 spent, with local variation in some places exceeding $16 saved

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Exceed common code requirements	Meet common code requirements	Utilities and transportation	Federally funded
Overall Hazard Benefit-Cost Ratio	4:1	11:1	4:1	6:1
Riverine Flood	5:1	6:1	8:1	7:1
Hurricane Surge	7:1	Not applicable	Not applicable	Too few grants
Wind	5:1	10:1	7:1	5:1
Earthquake	4:1	12:1	3:1	3:1
Wildland-Urban Interface Fire	4:1	Not applicable	Not applicable	3:1

FIGURE 1 Benefit-cost ratio (BCR) by hazard and mitigation measure. Source: MMC (2018).

per $1 spent. Figure 1 shows BCR values by peril and mitigation category.

An important goal of this study was to account as comprehensively as possible for benefits and costs, including reductions in property loss, deaths and nonfatal injuries, incidence of posttraumatic stress disorder (PTSD), direct and indirect losses from business interruption (BI), costs for urban search and rescue, insurance costs, and losses associated with environmental and historic impacts. Benefits are recognized for a reasonable lifespan of the mitigation measure (75–100 years, depending on the infrastructure), with three discount rates to account for the time value of money (real cost of borrowing, 3 percent, and 7 percent per year). Death and injury benefits were not discounted. Costs included up-front and long-term maintenance. However, some important nonmonetary benefits were not quantified, such as disconnection of victims from friends, schools, work, and familiar places; loss of family photos and heirlooms; harm to a place's culture and way of life; and other long-term consequences to health and well-being.

Comparison of "As-Is" and Resilient Water Supply Grid

While codes exist for building design, and that design can be enhanced by considering benefit-cost ratios, fewer codes exist for infrastructure, even though benefit-cost considerations can enhance their design. To assess the benefits of enhanced design, the MSv2 study examined BCRs for the following categories of infrastructure: water, wastewater, electricity, telecommunications, roads, and railroads. Four perils were considered: earthquake, flooding, wind, and fire at the wildland-urban interface (WUI). We discuss the study of the benefits and costs of implementing a resilient grid in an urban water supply network subjected to earthquake. That is, we consider whether it is cost effective to improve network resilience by reducing seismic vulnerability or otherwise improving all or some distribution trunk lines, thereby forming a resilient grid (Davis 2017).

A three-phase approach was used in the study:

1. Phase 1: The study examined an idealized water supply network, sized to be generally representative of a medium-sized US city, in order to draw general conclusions for cities in high seismic hazard locations. Figure 2 shows the schematic network, termed the *as-is network*, which was examined for earthquake resilience. The figure shows that a transmission line brings raw water from the source (a reservoir) to a treatment plant. Treated water is conveyed to terminal reservoirs and then the distribution network, where trunk lines convey water to distribution lines. (Some or all of the trunk lines can form the resilient grid.) The model region is square-symmetric to eliminate bottlenecks or other complicating factors. The size and spacing of distribution pipes and trunk lines accommodate typical average day demands including ordinary fire flows (figure 3).

2. Phase 2: The as-is network was stressed with random breaks and leaks resulting from earthquake excitation together with extraordinary fire demands (the phenomenon of fire following earthquake; TCLEE

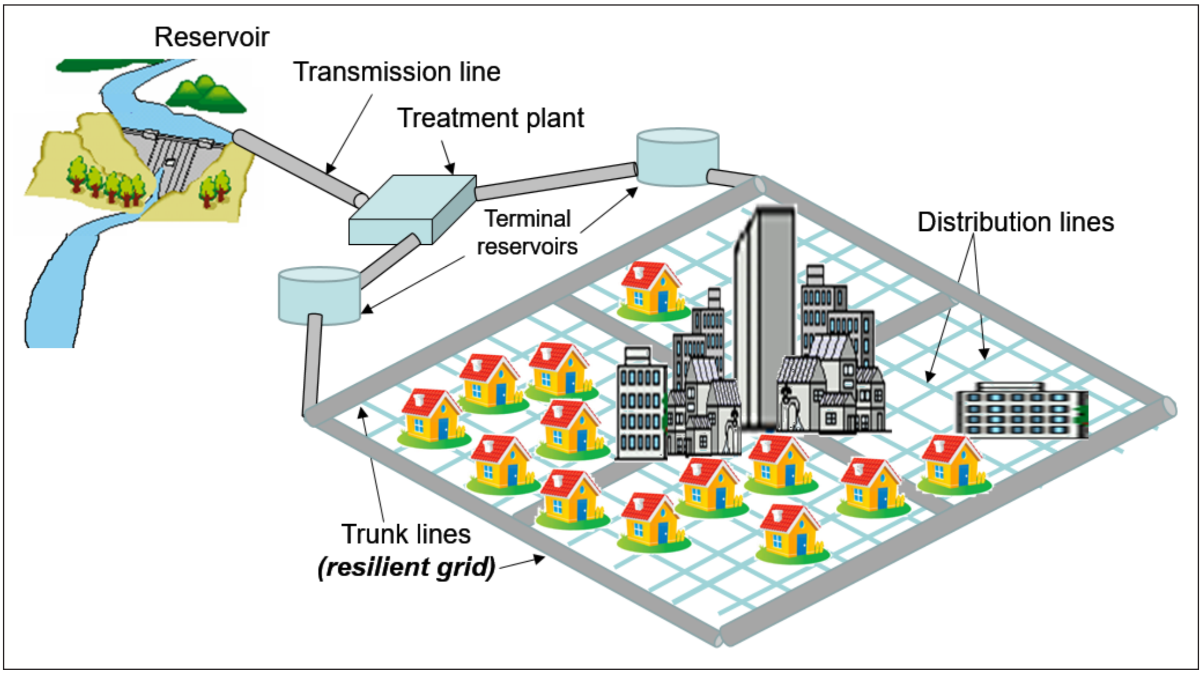

FIGURE 2 Schematic of "as-is" water supply network: transmission line brings raw water from source (reservoir) to treatment plant; treated water is conveyed via trunk lines to terminal reservoirs and then to distribution network. Some or all trunk lines can form the resilient grid.

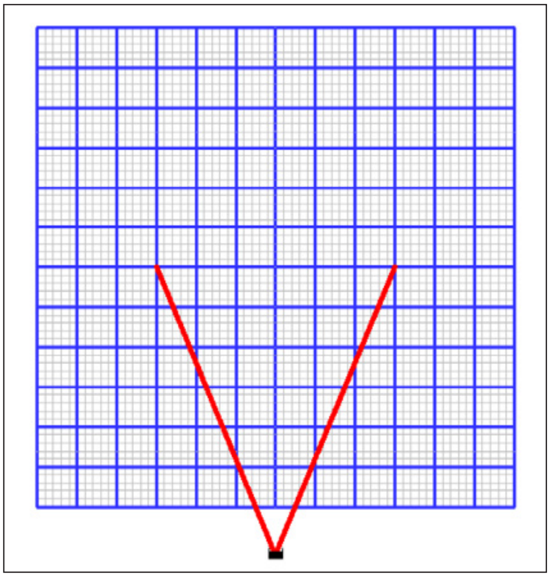

FIGURE 3 Study grid intended to be representative of the water distribution system of a medium-sized city. It is 36,000 ft (6.82 miles) on a side, with 61 lines of N-S and E-W distribution pipes regularly spaced 600 ft apart (grey lines). Trunk lines (the resilient grid), shown in bold blue, are placed every 5 distribution pipes, in a grid of 3,000 ft. The source (small black box), south of the grid, supplies two terminal reservoirs (at the upper ends of the red lines) placed symmetrically in the East and West parts of the city via transmission lines (red; the transmission lines are not part of the model). The distribution and trunk grids are connected only at intersections.

2005). Under earthquake excitation[2] the as-is water system, which was not designed with earthquake in mind, incurs repair costs as well as insufficient water pressure to both continue serving all its customers and provide firefighting water supply (figure 4), causing loss of service and leading to larger fires after an earthquake and longer time to recovery.

3. Phase 3: The as-is system was improved to form a resilient grid. The improvement consists of replacing selected trunk lines with lower-vulnerability pipe that experiences less damage when subjected to earthquake excitation. For example, cast iron or asbestos cement trunk lines might be replaced with earthquake-resistant ductile iron pipe (ERDIP). The shortfall (if any) and resulting consequences of this resilient grid system, stressed with the same scenario, were compared with those of the as-is system to determine benefits of the improvement.

The difference in loss of service, fire size, time to recovery, and costs between the as-is and resilient grids is a measure of the benefits of the resilient grid. These benefits include reduced losses in (a) water system

[2] Denoted using the Modified Mercalli intensity (MMI) scale, although calculations were performed using more detailed engineering parameters (see Porter 2018).

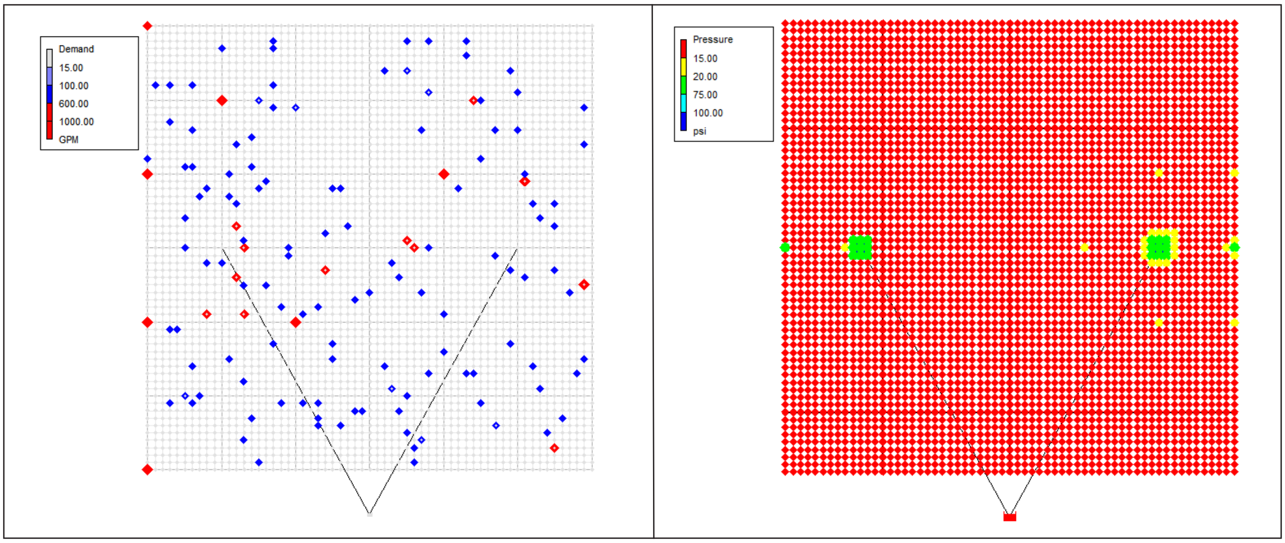

FIGURE 4 Under an MMI 8 earthquake the as-is design (left) sustains 111 distribution and 9 trunk line repairs (blue diamonds) and 21 ignitions (red diamonds, not all shown at this scale), changing the pressure distribution (right): red indicates nodes with inadequate pressure for firefighting, yellow barely adequate, and green adequate. Reprinted with permission from MMC (2018).

repair costs, (b) fire-related property losses, (c) direct BI associated with lack of water service and fire damage, (d) indirect BI losses for the rest of the economy that does business with customers who lose water service or suffer fire damage, and (e) deaths, injuries, and instances of PTSD resulting from fire after the earthquake. These benefits were then converted to equivalent dollar amounts per year by integrating benefits with hazard frequency.

Calculating the Financial Benefits of Resilience

The study team estimated the present value of benefits over a time horizon by applying a discount rate equal to the real cost of borrowing. The present value of benefits divided by cost was the BCR for the resilient grid, as shown in table 1, which presents BCRs for scenario events, and for four West Coast cities (table 2) considering their actual seismic hazard. As one would expect, table 2 shows that resilient infrastructure is more cost beneficial the greater the seismic hazard: San Francisco and Los Angeles, which have very high seismic hazard, benefit much more than, say, Portland (OR), where seismicity is more moderate (“moderate” as averaged over many years; it should be noted that Portland’s and Seattle’s seismic hazard is currently much greater than “moderate” because of an anticipated very large Cascadia Subduction Zone earthquake; see Atwater et al. 2015).

Study observations included the following:

- The major benefit of the resilient grid was due to improved supply of firefighting water.
- The benefit of the resilient grid was due to the lack of fire service capacity. If the fire service increased its capacity—for example, by moving water via tanker trucks or portable water supply systems—the resilient grid was less beneficial.
- The observation above reinforced the point that the resilient grid concept cannot be solely a water department initiative but needs to be pursued in close cooperation with the fire service.
- The resilient grid was quite likely to significantly reduce restoration time of the water supply to customers.
- Closer spacing of the resilient grid (e.g., trunk lines at every fifth or sixth distribution line rather than every tenth) may not significantly increase the BCR: although it increased benefits, it also increased costs.
- The findings on BCRs were based on the overly conservative assumption that the resilient grid required the replacement of 100 percent of the trunk lines. If only a portion of the resilient grid required replacement (e.g., 50 percent of the existing trunk lines were considered of low vulnerability and therefore did not require replacement), the BCRs would have been doubled.

As the study notes, the BCRs are based on long-term seismic hazard probabilities, not time-dependent prob-

TABLE 1 Summary of losses and benefits with and without resilient grid for a given earthquake ($ millions)

	Modified Mercalli intensity (MMI)				
	VI	**VII**	**VIII**	**IX**	**X**
Losses without resilient grid	none	$138	$19,007	$53,224	$152,774
Losses with resilient grid	none	$119	$8,667	$33,517	$132,993
Benefit of resilient grid	none	$19	$10,341	$19,707	$19,782
Cost of resilient grid	$403	$403	$403	$403	$403
Benefit-cost ratio	0	0.05	25.7	48.9	49.1

TABLE 2 Summary of benefit-cost ratios for several interest rates, four West Coast cities

Real discount rate (per annum)	San Francisco	Los Angeles	Portland OR	Seattle
2.17%	8.3	6.3	0.59	1.73
3.00%	6.4	4.9	0.46	1.34
7.00%	2.9	2.2	0.2	0.6

abilities. All four cities are judged to be at high risk of a major earthquake in the next several decades, which if considered would increase the BCRs significantly.

The Value of Pricing Risk

More resilient infrastructure design can clearly be achieved through the PBD approach, which is in the early stages of being implemented in a few infrastructure systems (Davis 2017).

For much infrastructure, however, the lack of standards vis-à-vis system performance given natural hazards means that resilience is not really considered. For example, electric power system reliability is measured using metrics such as the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) (IEEE 2012), but these are only empirical measures of past performance and don't consider prospectively the impact of catastrophic natural hazards. As a result, electric utilities and the public may be under an illusion about the reliability of electric power (Larsen et al. 2015; Mauldin 2015).

Costs of Externalized Risk

An extreme example is Fukushima, where TEPCO's pretsunami electricity pricing did not include a charge for the risk of meltdown and associated cleanup. Had such risk been priced into the cost, (a) TEPCO may well have found it cost effective to build better tsunami protection and (b) authorities would have had a reserve to pay for the postdisaster costs.

The same would apply for PG&E's electricity pricing in WUI areas: not only would such pricing apply to locals, but some charge would apply to the broader customer base for bulk transmission that creates risk in crossing the WUI to serve urbanized areas.

An example of risk charging in a changing environment is the increasing transportation of oil by rail in the United States. Accidents involving oil tank car trains can be very serious. The most well-known recent example was the July 2013 derailment in the Québec town of Lac-Mégantic of a freight train operated by the Montreal, Maine and Atlantic Railway (MMA). The accident killed 47 people and caused widespread destruction estimated in excess of $100 million.

The combination of increasing shipments by rail and the higher accident rate by rail (Mason 2018) has raised significant concerns about transportation safety and potential impacts to the environment (Frittelli et al. 2014; Hughlett 2019; IRSWG 2014; Millar 2018), although recommended fixes are so far limited to more frequent inspections and improved emergency response (IRSWG 2014). That is, the recommended fixes aim to make a disaster less likely to occur in the first place and to decrease the loss if it does occur, but they do not address the question of who bears the risk in these situations. While the oil and rail companies profit, and the general public benefits from the cost-effective distribution of energy, a disproportionate amount of the risk (virtually all) is borne by persons and property in direct proximity to the rail line (Gelfand 2018).

In economic terms, MMA externalized its risk: it imposed the negative outcomes of its cost-cutting practices on parties who did not choose to incur them.

Equitable Risk Pricing

Economists often urge governments to adopt policies that internalize an externality so that costs and benefits mainly affect parties who choose to incur them: when there is no externality, allocative efficiency is achieved. Internalizing risks also seems more equitable to outside parties.

One approach to encourage both risk equity and infrastructure PBD is the creation of a risk tax, analogous to the carbon tax (see www.carbontax.org) adopted by many industrialized countries.[3] Just as a carbon tax encourages carbon-reducing economic development and provides funding for carbon-reducing activities, a risk tax would encourage risk-reducing economic development and provide funding for risk mitigation. While the chances in the near term for a US risk tax are probably lower than for a national carbon tax, some states, communities, and enlightened corporations are implementing carbon-based taxing or policies,[4] so a path does exist. The concept of a risk tax deserves discussion.

Synthesis: A Spatiotemporal Model for Resilient Design

Most approaches to PBD and resilience are still rather parochial: building performance is typically decided only in the context of a particular building, and infrastructure performance only in the context of a single facility or, at best, the operator or agency. One might suppose that such an approach will still tend toward the greater good, based on the hypothesis that the invisible hand of the market (from Adam Smith's *Theory of Moral Sentiments* and *Wealth of Nations*) will produce nearly the same outcomes from economic actors such as MMA and PG&E as the companies might have produced from motives of pure humanity or justice. But the evidence from Lac-Mégantic, the 2018 California wildfires, and countless other examples undermines that hypothesis.

Recognition of the lack of this broader perspective and the failure of the invisible hand adequately to protect society from disasters is leading to demands for better longer-term systemic performance, such as Los Angeles' Resilience by Design program (Mayoral Seismic Safety Task Force 2014; and see Jones and Aho 2019 in this issue). What is required, whether for the urban fabric of buildings or for the system of urban infrastructure systems, is a recognition of the difference between the sum of failures of many buildings and infrastructure facilities in a community when treated as individually independent, and the totality of the impact of their simultaneous loss (considering correlations and negative synergies), as can and does occur in earthquakes, hurricanes, floods, and wildfires. The 2011 earthquake in Christchurch, New Zealand, Hurricane Maria (2017) in Puerto Rico, and the Paradise (CA) conflagration (2018) all bear witness to the compound effects of mass destruction. From a utilitarian perspective, PBD must count costs and benefits to all affected parties, not only developers, owners, or other authorities.

A risk tax would encourage risk-reducing economic development and provide funding for risk mitigation.

A PBD framework that considers the correlated effects of natural hazards, structural performance, and economics of all buildings in an urban region is needed. Theoretical models show that even small changes in the urban form, when regions of high hazard are considered, can greatly reduce urban lifecycle costs (Scawthorn et al. 1982). Even this approach has its limitations in that it is only a snapshot in time, and a more holistic PBD would consider natural disasters and recovery over time, explicitly accounting for resilience.

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[3] The current list is posted at https://en.wikipedia.org/wiki/Carbon_tax.

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Resilient communities have robust infrastructure and policies that consider the interconnections among people, hazards, and the natural and built environment.

Resiliently Engineered Flood and Hurricane Infrastructure:

Principles to Guide the Next Generation of Engineers

Gregory Baecher, Michelle Bensi, Allison Reilly, Brian Phillips, Lewis (Ed) Link, Sandra Knight, and Gerald Galloway


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The hurricane and flood disasters of recent decades have created a paradigm shift in how engineers approach natural hazards. The federal and some local governments have moved from standards-based approaches to developing risk-informed project plans, recognizing the importance of uncertainty in planning, the inevitability of disaster events, and the inability to provide absolute protection. Coupled with this is the concept of resilience—the ability of a system to function when exposed to disruptions—a concept long considered in ecology, sociology, and other disciplines.

As the 21st century presents both challenges from climate change and population growth and opportunities through technology acceleration, the task is to determine how engineers will leverage risk-informed approaches

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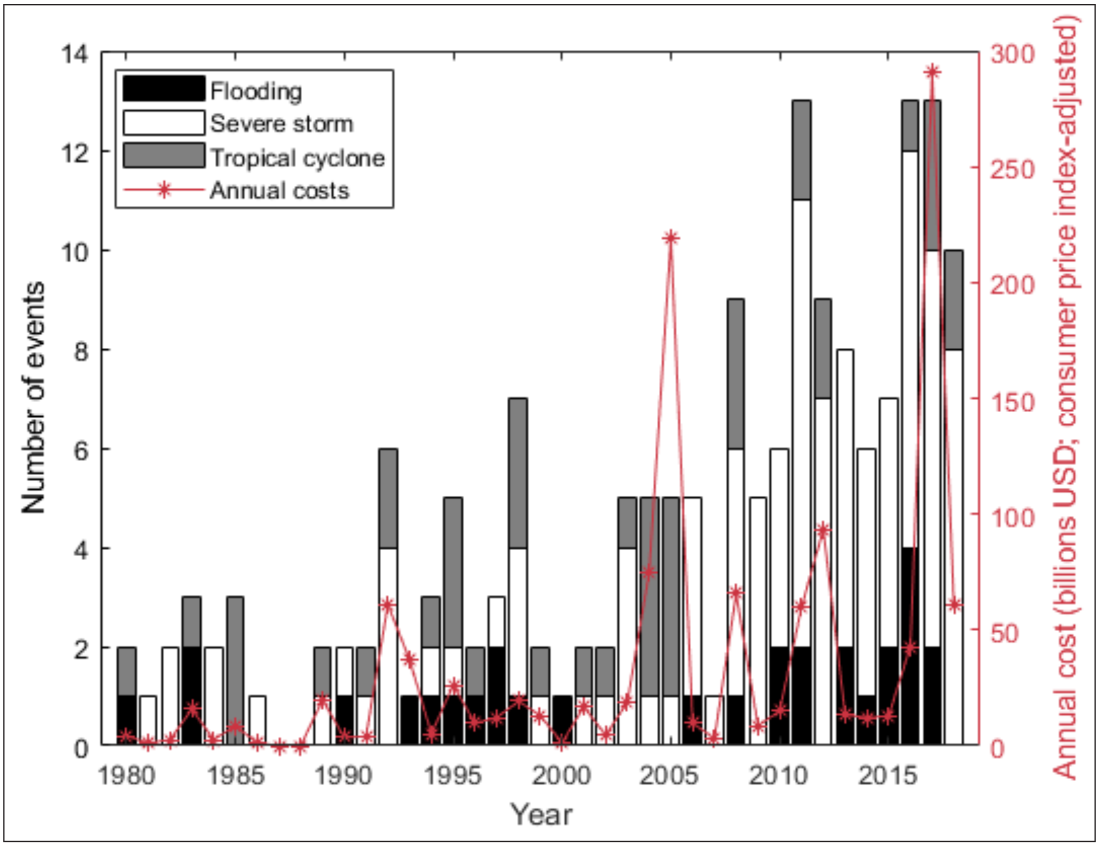

FIGURE 1 Hurricane, storm, and flood events exceeding $1 billion, 1980–2018. CPI = consumer price index; USD = US dollars. Figure adapted from NOAA/NCEI (2019).

to mitigate flood and hurricane impacts. This article discusses the transition from the 20th to a 21st century paradigm, and the impact of that transition on the education of engineers.

Background

The number and cost of disaster events in the United States has risen significantly over the past few decades (NOAA/NCEI 2019), and those related to floods and hurricanes are especially high (figure 1). For example, just since 2012

- the damage from Superstorm Sandy in 2012 was record-breaking in physical impacts and caused $47.5 billion in inflation-adjusted losses in New York and New Jersey.
- a 2014 pluvial flooding event in Michigan, caused by exceptional rainfall and inadequate drainage, was estimated to cost over $1 billion (NOAA/NCEI 2019).
- Hurricane Harvey in 2017 brought unprecedented rainfall, basinwide flooding, and windstorms that devastated infrastructure and flooded more than 150,000 homes, 46 percent of which were outside the FEMA 500-year floodplain (Galloway et al. 2018).
- Hurricane Michael, which devastated northwest Florida in 2018, was the strongest storm on record for that area and led to an estimated $25 billion in costs (NOAA/NCEI 2019).

These weather and climate events are diverse in their phenomenological origin as well as their impacts on communities. But it is expected that their frequency, severity, and cost will continue to increase because of climate change and factors such as land use and land cover changes, short-sighted planning and development, and federal disaster policy that emphasizes recovery rather than loss reduction.

The Transformation of Disaster Mitigation

During the 20th century engineering design primarily used resistance to minimize damage from natural hazards. Such designs provide adequate solutions when systems are exposed to hazards within the envelope of the scenarios and loads for which the systems were designed. However, when systems are exposed to scenarios that differ from those envisioned, resistance-based solutions are often inadequate. Moreover, such solutions are often associated with "cliff-edge" effects in which the adverse consequences of events may be exacerbated by changes in hazard conditions.

The escalation of disaster losses has resulted in recognition of the need for a 21st century paradigm that supports resilience for a broad range of evolving natural threats. A resilient community or organization is one that is prepared for hazard events, is able to respond and recover when events occur, and can adapt to changes in hazard exposure (NRC 2012). Resilience engineering is integral to this new paradigm: It approaches disaster loss reduction and avoidance using multifaceted approaches that cross traditional disciplinary boundaries.

Infrastructure systems must be designed in tandem with land-use planning, environmental consideration, and social and equity factors.

How can engineering accommodate the transition to a new paradigm, and what will be the impact of that transition on education? What steps is the profession taking to recognize the realities of hazards, understand how people and infrastructure respond to hazards, and work within resource limitations?

Engineering approaches to dealing with floods and hurricanes are constantly evolving, albeit in a reactionary way. Nations have moved from structural flood control to multiapproach flood damage reduction to flood risk management. After devastating losses in the Netherlands in 1953 from the North Sea flood and in the United States in 2005 from Hurricane Katrina, design approaches and engineering decision making began to change with new techniques. Safety factors have given way to reliability-based codes and are beginning to yield to performance-based analysis. The realization has come that there is no such thing as certain protection.

What Is Resilience Engineering?

The terms *resilience* and *resilience engineering* are used in a number of disciplines with definitions and approaches that differ by field and research focus. In general, resilience engineering focuses on

- the complexities of real-world systems (e.g., interdependencies, human-system interactions, and regulatory constraints),
- the evolving nature of hazards and systems,
- the strengths and limitations of conventionally engineered solutions, and
- the importance of working across disciplines to ensure that communities, organizations, and individuals are able to prepare for, respond to, recover from, and adapt to disruptive events.

These dimensions require new first principles to guide resilience engineers, as explained in a later section.

From the perspective of resilience engineering, a key element of resilient societies is functioning and reliable infrastructure to provide the essential services on which individuals, communities, and organizations depend. From transportation to health care, infrastructure comprises the facilities, systems, and networks necessary for society to function (DHS 2013). Yet many infrastructure systems are facing increasing service demands while deteriorating as a result of aging and inadequate maintenance (ASCE 2017).

Based on a new paradigm of risk-informed design and recognition of the interconnectivity of infrastructure and societies, infrastructure systems of the future will be designed differently, in tandem with land-use planning, environmental consideration, and social and equity factors. Risk will inform planning and decision making, and there will be greater integration of objectives with multiple attributes and more focus on lifecycle planning, flexibility and future options, and resilience.

How Does Resilient Infrastructure Differ from Today's Infrastructure?

In the past, infrastructure was designed to meet basic public needs using codes and guidelines. It now faces increasing natural hazards and other uncertainties, and must remain viable both in the face of such events and within a systems context.

Going forward, design and analysis decisions need to include social, economic, and environmental factors in addition to code requirements. Resilient infrastructure design must accommodate lifecycle relationships, consider destructive forces of natural hazards, incorporate end-of-use disposal, and be based on not only the engineering features but also the interrelationship among these features and other systems, including environmental systems. Furthermore, community, values, equity, and social responsibilities play increasing roles in engineering planning and design.

Because resilient development for a community or organization requires integration of the multiple sectors that support those entities, no aspect of infrastructure development can be accomplished in isolation (NRC 2012). Failure to incorporate social, environmental, economic, and engineering elements and to adapt to new technologies and approaches will limit, and perhaps even negate, the effectiveness of resilience efforts. To be successful, the engineering community must join other disciplines in eliminating silos in education, engineering, government, and other sectors.

Dealing with Complexities of Interconnected Systems

A particular challenge is that infrastructure systems may be distributed over large geographies, so their hazard exposure is greater than that of single-site facilities and they are exposed to a wider variety of hazards. Moreover, hazards can affect multiple components of an infrastructure system simultaneously. Neglecting to account for correlated loads and responses and for network effects and physical dependencies may result in inefficient allocation of resources and little improvement in system reliability.

While sector-specific interdependencies are often well known, cross-sector interdependencies are not. A failure in one sector typically leads to failures in others (Rinaldi et al. 2001), so infrastructure must be designed and regulated with consideration of both hazards and distributed network effects created by tightly coupled systems. Lifeline networks such as transportation, water distribution, and communications are particularly susceptible to natural hazards and may exhibit cascading failures.

Infrastructure is also broadly owned or managed by distinct owners and operators, and thus subject to many, at times conflicting, regulations. Planning objectives may focus on bettering one owner's system with little consideration of how it interrelates with other infrastructure and societal function. This leads to resource inefficiencies and stymies collaborative approaches to resilience. Current regulatory frameworks reinforce these tendencies by focusing on sector-specific performance (Reilly et al. 2015).

Moving Beyond Codes

The adoption and enforcement of building codes is left to individual states. In 2018 the Insurance Institute for Business and Home Safety ranked 18 Atlantic and Gulf Coast states on a scale of 0 (lowest) to 100 (highest) on the effectiveness of their residential building code adoption and enforcement programs (IBHS 2018). Scores ranged from 17 in Delaware to 95 in Florida, and the study reported that Alabama, Delaware, Georgia, Maine, Mississippi, New Hampshire, New York, and Texas have no statewide enforced residential building code.

Resilient infrastructure design accommodates lifecycle relationships, considers destructive forces of natural hazards, and incorporates end-of-use disposal.

Mitigation of damage from hurricanes will require more consistent adoption and enforcement of building codes. It is clear from recent hurricanes that buildings designed to modern codes demonstrate less frequent and less severe damage (IBHS 2004). Often simple solutions such as better window protection, stronger roof-to-wall connections, and stricter roof sheathing schedules significantly reduce wind-induced damage.

But current building codes do not address the uncertain hazard landscape of the future. Engineers need to better understand the impacts of climate change and how to adapt as it unfolds.

Current Tools and Principles

Design practice for water resources infrastructure has been based on either limits specified in codes or the best practice application of analytical tools using experience as a guide. While informed by statistical treatment of data, application of probabilistic methods has been limited to hazard characterization. Factors of safety have been the primary approach to dealing with uncertainty, which was seldom fully estimated or understood.

Hurricane Katrina and other major hazard events demonstrated the limitations of this approach and stimulated interest in adopting reliability-based approaches to improve planning and design.

Federal flood insurance rate maps (FIRMs) are the most common means of communicating flood hazard information. FIRMs delineate flooding hazards from fluvial and coastal flooding, but do not generally capture hazards from pluvial flooding or capacities of urban storm water systems to manage heavy onslaughts of water.

Most homes flooded during Hurricane Harvey were outside the FEMA-designated 500-year floodplain.

About 25 percent of all US flood insurance claims come from areas that FIRMs indicate have low to moderate flood risks (Galloway et al. 2018). In fact, most homes flooded during Hurricane Harvey were outside the FEMA-designated 500-year floodplain. Use of the FIRMs without recognition of their limitations may lead individuals, businesses, or communities to make suboptimal or even harmful decisions about mitigation and avoidance of pluvial flood hazards.

Hazard Characterization

Hurricanes, storms, and other meteorological events present complex threats. Floodwater-induced damage can be caused by surge, waves, inundation, and other effects (e.g., debris, sediment deposition, and erosion). Wind-induced damage results from wind pressure, debris impact, and wind-driven rain.

Hazard characterizations often focus on the meteorological storm (e.g., the Saffir-Simpson category of a hurricane[1]) or the total rainfall volume and intensities of storms. But the hurricane category or rainfall volume are incomplete characterizations of the forces that impact infrastructure and people—hurricane intensity does not accurately convey storm surge potential nor is rainfall fully representative of potential flood elevations for an area.

Datasets are available for tropical cyclone events, rainfall, and wind, but challenges arise when filtering these datasets for applicability to individual locations. Probabilistic hazard approaches are evolving to (a) integrate statistical analysis of historical data with physical process knowledge and models and (b) leverage new tools such as surrogate modeling based on machine learning methods (e.g., Jia et al. 2016) and ensemble modeling.

Moreover, while single hazard assessment approaches often dominate design, events may involve combined hazards, as in the case of Superstorm Sandy and Hurricane Harvey. There have been significant advances in characterizing hazard forces such as storm surge, particularly in terms of coastal geometry, storm path, and storm metrics beyond central pressure deficit.

High-resolution computational grids and depth-limited two-dimensional circulation models coupled with sophisticated wave models have raised the bar considerably. These model packages have been applied to ensembles of hypothetical hurricanes to develop distributed hurricane storm surge datasets for application with joint probability methods to advance both probabilistic hazard definition and risk assessments (Irish et al. 2009). This combined approach was a fundamental tool for the postevent analysis of Hurricane Katrina and the development of distributed risk estimates to inform the design of new risk reduction structures that were completed in 2011 (IPET 2009, p. 61).

Climate change is expected by many researchers to alter the frequency, duration, and intensity of North Atlantic hurricanes (e.g., Cui and Caracoglia 2016; Mallakpour and Villarini 2015; Webster et al. 2005). Warmer sea surface temperatures will extend the Atlantic hurricane season and broaden the area over which hurricanes form and strengthen. Climate change is already bringing wetter hurricanes (figure 2), with greater storm surge and freshwater flooding.

Increased sophistication in the application of probabilistic risk analysis to flood risk reduction provides a more comprehensive picture of near-term situations and significantly aides decision making. However, *nonstationarity* is of growing concern with hurricanes and floods. Nonstationarity can be briefly defined as changes in long-term means and other trends. Although risk analysis techniques can, in principle, be used to grapple with it, they have not been. Furthermore, while nonstationarity is often associated with climate change, other forms—such as changing land use, population, and property values—are also relevant.

[1] This is the wind scale ranking behind the designation of, for example, a Category 4 hurricane.

One option to deal with limited data, uncertainty, and nonstationarity is scenario analysis. An example of this approach is the Netherlands' Delta Program, which uses adaptive scenarios to deal with the implications of climate change for water management.[2] The scenarios explore four types of future situations to determine where and when alternative measures will be required in the future.

New First Principles of Resilient Design

Resilient infrastructure design requires a focus on first principles of a new paradigm. Whereas earlier generations of engineers were trained in balancing loads versus capacities and in optimizing benefits versus costs, resilience engineers will need to use the first principles of resilient design:

- integrate physical and social design considerations,
- quantify and incorporate uncertainty,
- use systems-level thinking and planning for diversity and redundancy,
- explicitly include options and adaptability in design decisions, and
- leverage nonstructural and nature-based alternatives.

Integration of physical and social design considerations requires that behavioral responses and vulnerabilities be incorporated explicitly in planning and design. Engineers must recognize and embrace the knowledge that effective resilience means that not only physical systems but also individuals, communities, and organizations can cope with and respond to disasters.

Creating resilient communities entails enhancing and building adaptive capacities through investments in preparedness and understanding the social factors that mediate community response. While engineers are not typically trained to have in-depth knowledge of these social dimensions and the need for community engagement, it is important that they understand the need to consider these factors and seek support and guidance from experts in the social sciences, economics, citizen outreach, and related fields as part of design and planning processes.

Recognizing and accommodating uncertainty is central to the principles above but remains challenging because of a lack of both guidance on standard tools and understanding of nonstationarity. Resilience engineers must consider systems-level interactions in design and plan for diversity and redundancy. Understanding such interactions means understanding system interdependencies and how humans and physical systems interact. Redundancy means that parallel and independent means are adopted. The inclusion of options and adaptability in planning allows for flexibility to cope with uncertain futures; scenarios of how the future might unfold provide a platform for including future options.

[2] https://www.government.nl/topics/delta-programme

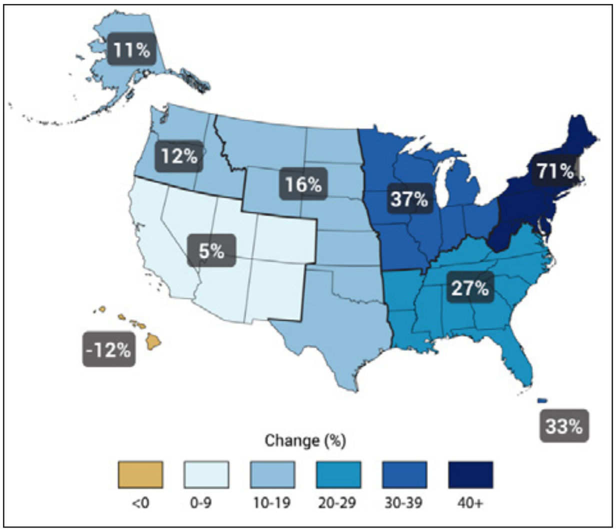

FIGURE 2 Percent increases in the amount of precipitation falling in the heaviest 1% of all daily events from 1958 to 2012. Source: Melillo et al. (2014). In parallel to increases in hazard frequency and intensity, population exposure is on the rise through coastal development and densification.

Nonstructural interventions and nature-based design increase resilience by reducing the consequences of flooding rather than its probability (the latter is commonly the goal of structural measures such as levees and seawalls). Nonstructural measures might include modifications to public, regulatory, or pricing policy in the National Flood Insurance Program; buyouts and relocations; changes to land-use regulations and permitting; flood proofing of structures; warning systems; and preparedness planning. Nature-based measures might include preservation of wetlands, development of vegetation dams on dunes, introduction of aquaculture, reforestation, and park creation along waterways (Bridges et al. 2015, p. 479).

Educating Resilience Engineers

The need to train the next generation of engineers for resilience faces an old tension in engineering education: the balance between breadth and specialization.

Undergraduate engineering programs must maintain broad traditional disciplinary coverage at appropriate depth while both incorporating emerging areas such as data science and computing and adhering to the broad and demanding requirements of professional associations like ASCE, accrediting authorities such as ABET, and professional licensure.

To address the needs of engineering for resilience, programs must add exposure to the social sciences, uncertainty and risk analysis, economics and finance, ecological engineering, and decision making under uncertainty. This is a substantial challenge. Moreover, strategies for engineering for resilience continue to evolve, requiring curricula that can be adapted to this changing knowledge base. Finally, administrative and financial barriers often exist when students are encouraged or required to take courses across conventional academic divides.

Engineering education programs must add the social sciences, uncertainty and risk analysis, economics, ecological engineering, and decision making under uncertainty.

New administrative strategies and a reimagining of curricula (e.g., through development of new courses that transcend conventional engineering silos) are needed to ensure that academic programs offer a more comprehensive, up-to-date undergraduate curriculum while remaining sensitive to the rising costs of education. Finally, educators must carefully consider whether master's-level engineering specialization is needed to prepare competent resilience engineers.

Conclusions

Infrastructure needs have traditionally been addressed with assumptions and practices that oversimplify uncertainties underlying complex interactions among social, environmental, and physical domains. Engineers have assumed stationarity, relied on short datasets, applied one-size-fits-all standards and factors of safety, and generally designed and built for "human" increments of time.

Knowledge has grown and demands on infrastructure have changed, and current approaches and tools do not meet the challenges of the future. The concept of major hurricane and flood risk reduction infrastructure projects with an *n*-year life, designed for a very specific set of loads and demands, is contrary to the increased pace of change and inherent uncertainties in the three domains. What's needed is a paradigm shift to engineering that embraces uncertainty and exploits multifaceted scenario planning and analysis, leading to incremental adaptive designs and infrastructure.

The shift toward this new paradigm is underway. The new risk reduction infrastructure in New Orleans incorporated uncertainty in the fundamental design; probabilistic approaches were used to reduce risks associated with overtopping and catastrophic breaching. But far from being a model for future design, it only addressed contemporary challenges. And as with all new paradigms, it creates conflict and confusion with respect to existing standards and practice as well as educational content.

The Netherlands' Delta Program and Delta Model initiatives incorporate risk analysis in a multifaceted scenario analysis that includes social, environmental, and physical factors to develop one of the first examples of a risk-informed, large-scale, adaptive strategy for changes in the water regime due to social/cultural and climate changes. The program depends, however, on avoiding unreasonable restrictions on the magnitude of the changes examined in the scenarios, which can limit the infrastructure approaches (structural and nonstructural) considered for adaptation. This could be a significant challenge to achieving the necessary paradigm, given the propensity of current practice to simplify and optimize based on limited resources, time constraints, stove-piped organizational responsibilities, and convoluted governance systems.

Ultimately, any approach that is adopted must recognize that a cornerstone of resilient communities is robust infrastructure and infrastructural policies that consider the interconnections among people, hazards, and the natural and built environment.

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A NIST assessment of lifeline infrastructure performance proposes prioritized actions to advance policy, modeling, systems operations, and research.

Increasing Community Resilience Through Improved Lifeline Infrastructure Performance

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The concept of community resilience is complex and multidimensional, relying on engineering and other disciplines to help communities break the cycle of destruction and recovery and reduce the impacts of earthquakes and other hazards. This article presents proposed prioritized actions to improve lifeline infrastructure resilience based on an assessment of lifeline infrastructure performance commissioned and funded by the National Institute of Standards and Technology (NIST).

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Introduction

Resilience involves the ability of people and communities to adapt to changing conditions and to withstand and rapidly recover from disruptions (White House 2011). At the community level, this concept is complex and multidimensional, relying on contributions from the social sciences, engineering, earth sciences, economics, and other disciplines to improve the ways communities prepare for, resist, respond to, and recover from disruptions due to either natural hazards or manmade causes. Resilience is intended to reduce both the impact of hazards by restoring community functions within a specified timeframe and the duration and cost of recovery. This requires planning for recovery and restoration prior to hazard events.

Disasters interfere with electric power, natural gas and liquid fuel, telecommunications, transportation, and water and wastewater infrastructure systems. Such systems are commonly referred to as "lifelines" because they are vital for the economic well-being, security, and social fabric of the people they serve (NIST 2014).

Lifeline systems are often distributed over large geographic regions and have numerous interdependent levels of operation, making them especially exposed to the impacts of earthquakes, hurricanes, and other hazards that affect broad areas. They are therefore vulnerable to distress and malfunction at many locations, which, in turn, impedes response and recovery. Lifeline infrastructure system failures and disruptions displace people, obstruct social and economic institutions, and in the worst cases lead to death and long-term negative societal consequences.

The NIST study overviewed in this article (a) assessed societal expectations of acceptable lifeline infrastructure system performance levels and (b) proposed actions pertaining to policy, modeling, systems operations, and research needs that will facilitate improved lifeline infrastructure performance during disasters.

The NIST assessment was carried out to inform users of the *Community Resilience Planning Guide for Buildings and Infrastructure Systems* (NIST 2016a), which provides a practical and flexible approach to help communities improve their resilience by setting priorities and allocating resources to manage risks for their prevailing hazards. The assessment is described in detail in the NIST (2016b) report, *Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster Recovery*.

Background

We begin with an overview of (a) the current state of lifeline infrastructure design and construction codes, standards, guidelines, and performance requirements; and (b) impacts of disasters on lifeline infrastructure systems.

Codes and Standards of Practice

Codes, standards, guidelines, and manuals that govern the design, construction, and performance of lifeline infrastructure systems and components vary considerably from system to system and represent various levels of consensus, typically among operators, regulators, and engineering experts.

Variability in Requirements and Enforcement

Performance requirements in codes and guidelines focus mainly on engineering for system design, construction, and operation and tend to emphasize minimum levels of safety or the performance (e.g., for extreme loading conditions) of components as opposed to system response and levels of service. Most address day-to-day operations and do not cover the full range of hazard types that affect infrastructure systems, particularly low-probability, high-consequence events.

Lifeline infrastructure systems are often vulnerable to distress and malfunction at many locations, impeding response and recovery.

For electric power, natural gas, and liquid fuel systems, certain measures of system performance are routinely assessed and even required to be reported to regulators. But these measures generally address outages during normal operations and often exclude disruption caused by hazards. The three systems have regulatory data requirements for safety and reliability, and for gas and liquid fuel pipelines there is a national regulatory framework defined by federal legislation. Federal regulations also guide telecommunication systems.

While most US jurisdictions adopt the latest codes and standards and some add more stringent requirements to them, others may not adopt them in their entirety or may even reduce some requirements. Even if codes and standards are adopted, their effectiveness may be compromised by poor enforcement during the planning, design, and construction of infrastructure components. This disparity in code adoption and enforcement can significantly degrade community resilience through regional dependencies and cascading consequences.

Societal Considerations

Codes and standards give the greatest emphasis to failures in particular infrastructure systems (e.g., natural gas, liquid fuel, transportation) and to infrastructure service outages (e.g., power, telecommunications [911], natural gas, water, wastewater) that can contribute to mortality and morbidity. They also take into account different but more limited societal considerations such as life safety, public health, emergency response, critical service provision, property and monetary loss prevention, and environmental protection.

The effectiveness of codes and standards may be jeopardized by poor enforcement during planning, design, and construction.

As discussed below, most system performance measures are not informed directly by or linked to societal expectations and needs. The direct and indirect costs to customers will likely vary with the duration of system disruptions (i.e., mere inconvenience in the first few hours to severe hardship after weeks of lost service), but system performance measures rarely consider the differential hardships imposed on society from varying durations of outage.

Disaster Impacts on Specific Infrastructure Systems

There is a substantial body of literature on the social and economic impacts of infrastructure service disruptions, spanning studies on actual events—both hazard and nonhazard related—and scenario-based and probabilistic loss projections. Most studies of disaster-related impacts on infrastructure systems are event specific; systematic, multievent studies are generally rare. Also, in general there is more information and a better understanding of the societal impacts and restoration patterns of short-term rather than longer-term disruptions. We briefly describe disaster-related impacts on several types of lifeline infrastructure.

Electric Power

Most major and widespread electric power outages are due to storms or other weather events, and there are more data on such events than other hazards, particularly the technical aspects of component and system failure and restoration. Common information for electric power performance in hazard events includes standard industry measures, peak number of customers without service, and time to restore service to all (or nearly all) customers.

Gas and Liquid Fuel

Gas and liquid fuel production, transmission, and distribution systems are susceptible to damage in most hazard events. Loss of power to oil refineries and pipeline pump stations during high wind and coastal inundation events causes loss of production and transmission, interrupting fuel supply for businesses and consumers. After Hurricane Sandy, for example, disruptions at nearly every level of the fuel supply chain reduced all fuel flow into and within the New York City metropolitan area.

Ground faulting and liquefaction caused by earthquakes can lead to the rupture of gas and fuel pipelines, but appropriate design measures can mitigate these effects, as demonstrated by the good performance of the Trans-Alaska Pipeline System during the 2002 Denali Fault earthquake (Hall et al. 2003).

But the fact that some lifeline infrastructure systems are confined within states and others distributed nationally leads to differential impacts. The spatial distribution of the nation's natural gas delivery system, for example, is nationwide (figure 1). Pipelines originating in Louisiana and crossing the Mississippi Valley convey natural gas for heating and cooling in heavily populated areas of the Northeast and Midwest. They are subject to disruption by hurricanes, river flooding, and earthquakes that originate in the New Madrid Seismic Zone, which crosses Kentucky, Missouri, Tennessee, and Arkansas.

Moreover, some locations are serviced by a single pipeline. For example, more than 90 percent of refined petroleum products bound for Portland, Oregon, follow a single route that is at risk from liquefaction-induced ground failure during an earthquake as well as from hurricanes and floods (NIST 2016a).

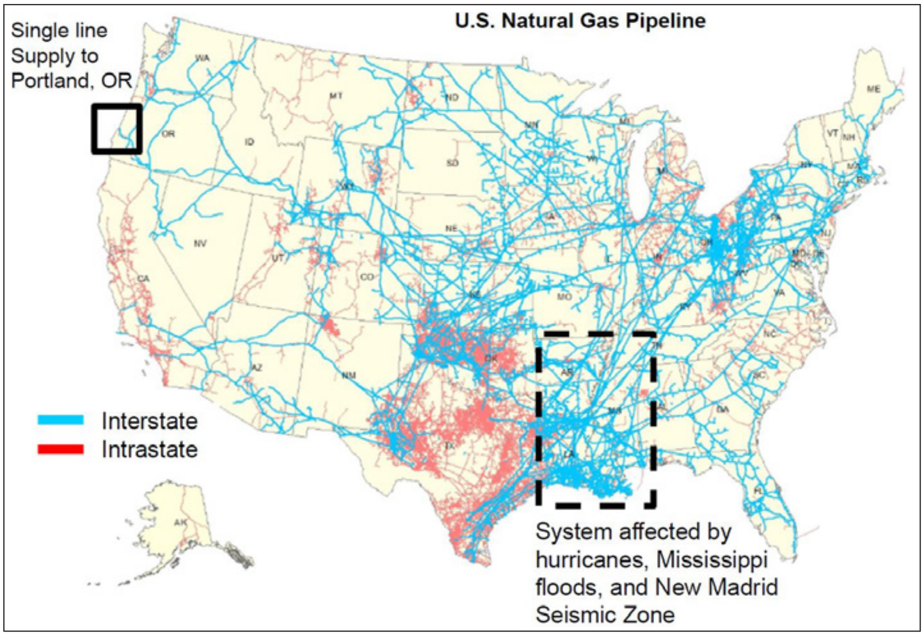

FIGURE 1 Map of US natural gas interstate and intrastate transmission system. Source: NIST (2016b).

Transportation

Transportation systems are susceptible to damage or disruption due to a variety of natural events. Common earthquake damage includes bridge failures (figure 2) and landslides that can hamper emergency response, particularly to remote communities. Scour induced by inundation or flooding can also result in bridge, rail, and roadway failures.

Weather events involving wind, snow, and ice can cause disruptions but physical damage tends to be more limited, so data on transportation performance in earthquakes, tsunamis, coastal inundation, and riverine flooding are more readily available.

FIGURE 2 Collapse of Hanshin Expressway elevated highway bridge during the 1995 earthquake in Kobe, Japan. Photo by C. Rojahn.

Water and Wastewater Systems

Water and wastewater systems are susceptible to damage during earthquakes, tsunamis, and other forms of inundation. Disruptions to water supplies can have serious impacts on fire-fighting capacity and sanitation with adverse public health, safety, and economic consequences.

Water service restoration times for Los Angeles after the 1994 Northridge earthquake, for example, are shown in figure 3. They varied significantly for different services (Davis 2014; Davis et al. 2012). Restoration of potable water to households and the fire department, for instance, lagged that of nonpotable water deliveries and normal quantity. And a return to preevent system functionality, as well as achievement of improved reliability, was a long-term process that lagged the restoration of other services and actually required many years to achieve.

Overarching Societal Considerations

Most infrastructure system outages last from hours to weeks (short- to intermediate-term recovery). In severe cases, outages can last for months or even years. Long-term outages are associated with the most destructive events, when critical, large, and/or multiple components of lifeline infrastructure systems that are time consuming to replace—such as bridges, piping, and essential equipment—must be reconstructed or replaced to restore system operability.

Societal Expectations and Tolerance

Empirical data on public expectations of acceptable infrastructure performance after disruptions are

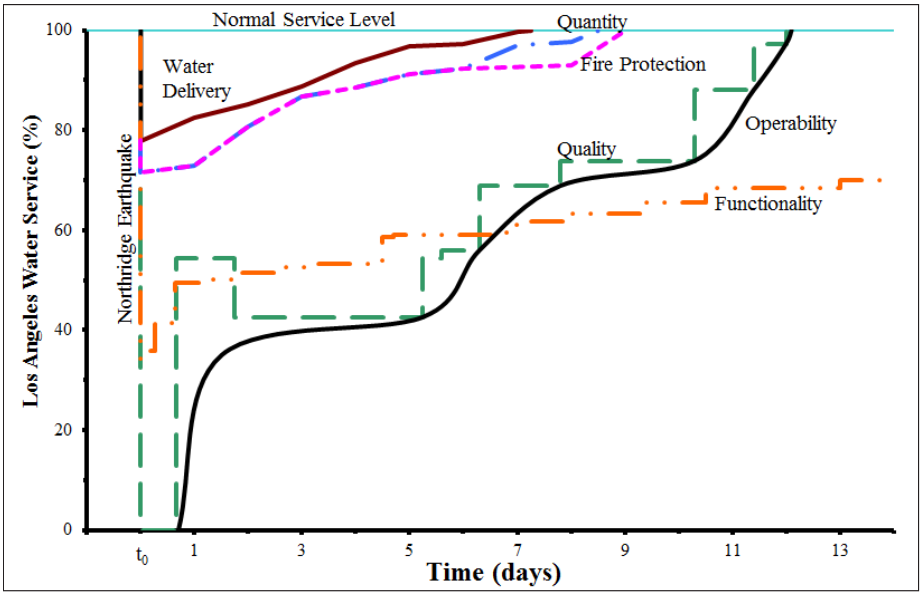

FIGURE 3 Los Angeles water system service restorations after the 1994 Northridge earthquake. Reprinted with permission from Davis (2014).

sparse, and gauging societal expectations is challenging because US society is highly diverse. Expectations vary among individuals, households, and businesses as a function of a number of factors, such as vulnerability and resilience characteristics; geographic location; hazard characteristics (e.g., severity, probability, and duration); infrastructure type; available information on the impacts of disruption; prior experience and knowledge about service disruptions; levels of resulting losses; public perceptions of the trustworthiness and competence of service providers; and availability of substitutes and contingencies that can compensate for system outages.

Additionally, there is evidence to suggest that societal expectations and tolerances may be changing as social and economic activity becomes more dependent on highly reliable service provision, particularly electric power and telecommunication systems.

One approach to assessing likely societal expectations is to look more closely at how infrastructure performance and disruption can have deleterious effects on what society members value most. This approach is consistent with NIST (2016a), which uses Maslow's "hierarchy of needs" framework to prioritize different building and infrastructure systems in communities. For this reason, human health and safety, the functionality of healthcare systems, and economic well-being are deemed priority areas when exploring societal considerations regarding performance.

Risk Perception and Communication

Public expectations and tolerances for infrastructure service disruptions are dynamic and likely to be shaped by both risk perception and risk communication. Factors that affect risk perception include prior experience with hazards and outages, substitutability and dependency on lost services, and available information about the impacts of disruption.

Other things being equal, disruptions may be tolerated for longer periods in severe and catastrophic events than in less serious ones, because the public will be more willing to accept the difficulties that extreme hazard events pose for service providers to anticipate and mitigate. Public confidence and the past performance of infrastructure service providers (during both routine operations and hazard events) can also influence expectations and tolerances.

Public perceptions and expectations are also shaped by communications about the risks associated with past disasters and outages. Infrastructure system service providers can work with emergency management, public safety, and other governmental agencies to ensure that risk communication messages reach and are understood by the affected public.

Differential Vulnerability

Various segments of the population and sectors of the economy are differentially exposed, sensitive, and adaptable to infrastructure service disruptions. Risks associated with infrastructure service disruptions are not borne equally by all members of society but are imposed disproportionately on already vulnerable social and economic groups.

Infrastructure Interdependency Considerations

Dependent and interdependent relationships among infrastructure systems have evolved over time, with various systems and technology advances expanding and linking systems together. The NIST (2016b) assessment considered interactions among different infrastructure systems during normal operations and restoration after hazard-related events.

Interdependency mechanisms broadly classified as physical, geographic, cyber, and logical are not necessarily mutually exclusive (Rinaldi et al. 2001):

- Physical interdependence: the performance of one network depends on the outputs of others.
- Geographic interdependence: systems are colocated or in close proximity.
- Cyber interdependence: the interdependence between two networks is based on shared information (e.g., the "smart grid," which relies on telemetry and situational awareness data).
- Logical interdependence: systems are interconnected through channels different from the preceding three, for example based on human decisions related to restoration prioritization among systems.

The NIST assessment revealed critical dependencies and interdependencies across infrastructure systems. Virtually every infrastructure system today depends on electric power and telecommunications for control and monitoring. All infrastructure systems also depend on fuel and transportation, particularly for service restoration and system repairs. Fuel is a critical contingency for power when outages occur. Water is critical for cooling in the generation processes for electric power. Water also helps with pollution control and supports other infrastructure, such as natural gas and liquid fuel systems.

Some interdependencies are increasing, as evidenced by the expanding role of telecommunications and electric power in monitoring and remote control of infrastructure systems as well as household management, personal choices for renewable power, and community planning for decentralized energy. A simplified set of dependencies for communication systems is shown in figure 4.

The physical proximity and colocation of multiple infrastructure systems can enhance efficiencies but also increase risks of cascading failures and complex interactions in restoration, as well as risks posed by multihazard effects.

Interdependent systems may also require a cross-system, cross-organizational, and integrated approach to planning that is difficult to implement. And choke points may amplify interdependencies within systems as well as between infrastructure systems and community-level processes.

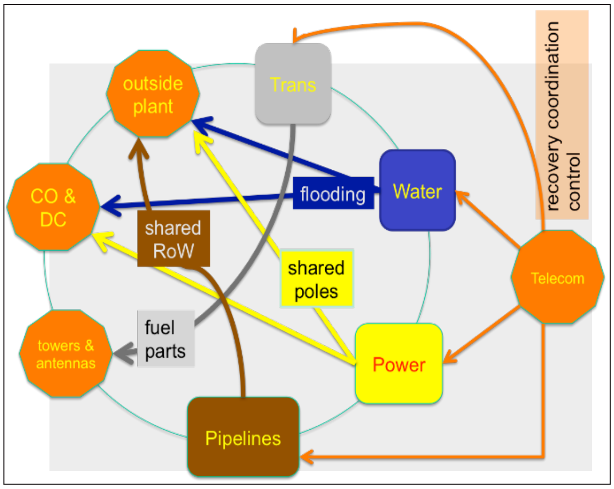

FIGURE 4 Simplified illustration of telecommunication interdependencies. Orange decagons = telecom-related components; rounded rectangles = other critical infrastructures and how they can impact aspects of telecommunication systems. For example, water main breaks may flood central offices (CO) and data centers (DC). RoW = right of way; trans = transmission. Source: NIST (2016b).

Proposed Actions for Improving Lifeline Infrastructure Performance

Infrastructure resilience is clearly essential to the country's economic and social well-being. And according to the National Institute of Building Sciences, the nation saves $4 in future disaster costs for every $1 invested in utility and infrastructure mitigation activities (MMC 2018). The federal Disaster Recovery Reform Act, signed into law in October 2018, established a National Public Infrastructure Pre-Disaster Hazard Mitigation Grant Program for public infrastructure projects to increase community resilience before a disaster occurs.

In this context, the NIST (2016b) assessment identifies and prioritizes needed improvements to codes, standards, and guidelines; modeling; system operations; and proposed research topics.

Codes, Standards, and Guidelines

Ten actions, in ranked order, are proposed to address needs related to codes, standards, and guidelines that govern the design, construction, and performance of various lifeline infrastructure systems ("lifelines") and system components. The priority rankings reflect organizational and framework needs, available information, new knowledge needs, guideline and standards development needs, and scoping breadth. Proposed actions pertaining to broad issues and improved community resilience have higher priority than proposed actions for specific lifelines.

1. Identify or establish an organization and process for advocating, harmonizing, and unifying consensus procedures for lifeline guidelines and standards development.
2. Develop more consistent terminology for lifeline standards.
3. Develop an up-to-date and complete suite of codes, standards, and guidelines for all lifeline systems to reflect the current state of practice, knowledge, and performance requirements.
4. Develop a methodology to combine component-based design criteria with system-level performance targets.
5. Develop lifeline system performance requirements that relate to community resilience and better reflect societal considerations.
6. Develop consensus-based guidelines and standards for the design of new lifelines and the retrofit of existing lifelines to reflect community resilience performance requirements and societal considerations.
7. Develop guidelines to inform the design, interoperability, and upkeep of lifeline system dependencies.
8. Reduce inconsistencies in codes and standards for the design, construction, and resilience of the built environment (e.g., fire codes, building codes, and codes, standards, and guidelines for lifeline systems).
9. Develop consistent policy and standards on accessing information and databases about critical infrastructure systems that are coordinated with activities of the Department of Homeland Security.
10. Provide updated guidance for evaluating gas and liquid fuel pipeline and facility response to seismic hazards, floods, coastal storms, and tsunami-related inundation.

Modeling

System modeling for lifeline systems and their interdependencies can be leveraged to improve resilience across such systems. The following proposed improvements to address limitations in scope, outputs, integration, and validation are considered high priority.

1. Aggregate existing infrastructure modeling tools and create a user-friendly interface so communities can properly assess their lifeline-related system performance and restoration risks, including uncertainty.
2. Develop first-generation models and practical tools for community resilience analysis that account for lifeline system dependencies and interdependencies.
3. Improve numerical modeling of water and wastewater systems, with emphasis on validation of models, development of the most effective simulation procedures, and applications in real systems.

Infrastructure System Operations

The following proposed high-priority actions address needs related to lifeline system operations and operational design. These needs must be addressed to improve community resilience and bridge the gap between the postevent capabilities of lifeline systems and societal expectations of their performance and restoration.

1. Develop a process for major utilities to conduct self-assessments of their preparedness for various natural hazard events, as a basis for prioritizing improvements to system robustness and postevent response.
2. Develop guidance for lifeline service providers on how to engage and collaborate with communities, including emergency management agencies and other key community institutions, in developing resilience strategies and preparing system restoration and contingency plans.
3. Develop guidance for local planning (e.g., for fuel delivery to emergency responders and critical infrastructure).
4. Develop guidance for lifeline service providers to evaluate the effects of system component failures, both in isolation and in combination, and considering upstream and downstream dependencies.
5. Design protocols for lifeline service providers, working with emergency management and other community institutions, to communicate to the public the likely impacts of different hazard events on service provision and disruption.

Research

Fifteen research topics are proposed to address gaps in data and knowledge needed to improve understanding of acceptable infrastructure performance. All the topics are considered high priority.

1. Gather information on and systematically study the relationships between service disruptions and societal impacts and expectations to better understand lifeline system performance.
2. Assess societal expectations associated with lifeline system performance.
3. Systematically study and compare design approaches and methods for addressing societally based performance requirements as set forth in current codes, standards, and guidelines for lifeline systems.
4. Investigate the differential vulnerability among social groups to lifeline system outages.
5. Systematically collect and review various "proxies" and secondary evidence for societal expectations of lifeline performance and restoration timeframes.
6. Assess lifeline performance programs and practices for public safety and develop guidance on their application to other critical lifelines, including multiple, interdependent systems and colocated facilities.
7. Conduct research on needed service restoration times, including the role of system operability, as a performance metric, in supporting community resilience.
8. Study lifeline system operator organizational issues and how they affect community-scale lifeline performance and resilience planning.
9. Enhance understanding of infrastructure-related failures and cascading effects from low-probability/high-consequence events.
10. Develop postevent data collection protocols to assess lifeline system recovery and restoration timeframes and improve understanding of restoration processes across individual and interdependent lifeline systems.
11. Develop tools to identify (a) interdependent infrastructure systems and services and (b) their restoration criteria.
12. Establish procedures to quantify hazards for spatially distributed systems.
13. Enhance understanding of lifeline system supply sources and endpoint facilities and their role in system performance, restoration, and community and regional recovery with the goal of improving databases and modeling of such sources and facilities.
14. Study changes in water demand considering an array of hazards as well as seasonal and longer-term climate variability (e.g., drought).
15. Improve knowledge, databases, and modeling for impacts of widespread flooding and storm damage on regional fuel supplies.

Conclusion

The NIST assessment of lifeline system performance identifies a number of significant deficiencies in the current state of lifeline infrastructure design and construction codes, standards, guidelines, and performance requirements. It proposes prioritized actions to advance policy, modeling, systems operations, and research. In these ways it provides a roadmap to ensure that future investments in infrastructure resilience not only improve lifeline infrastructure performance during disasters but also better match societal expectations of acceptable system performance.

Acknowledgments

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A new computational environment provides comprehensive modeling to enhance understanding of decision points, actions, and resources for communities to improve their resilience.

A Fully Integrated Model of Interdependent Physical Infrastructure and Social Systems

Bruce R. Ellingwood, John W. van de Lindt, and Therese P. McAllister

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Common to the many definitions of resilience in the literature and in policy statements is the notion that resilience is *the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions*. The performance of the built environment and the support of social, economic, and public institutions are essential for a community's immediate response and long-term recovery after a disruptive natural hazard event.

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This article describes research in the Center for Risk-Based Community Resilience Planning, which is sponsored by the National Institute of Standards and Technology (NIST). The Center's objective is to advance measurement science to (a) understand the factors that make a community resilient, (b) assess the likely impacts of hazards on communities, and (c) develop risk-informed decision strategies that optimize planning for and recovery from natural hazard events. Research has already laid the groundwork for advances in community resilience science and implementation.

Introduction and Background

The resilience of a community is determined by its ability to return to a level of normalcy within a reasonable time after a disruptive hazard event; it reflects the community's preparedness and capacity to respond to and recover from damage to physical, social, and economic systems.

Community resilience needs are not generally reflected in the codes, standards, and other regulatory documents that engineers typically use.

Civil infrastructure, on which the economic and social well-being of any community depends, is susceptible to damage due to natural hazards such as hurricanes, floods, tornadoes, earthquakes, and wildland-urban-interface fires. Significant damage may occur even from hazard events with less than "design-level" forces, and may produce disproportionate economic and social losses, especially for lower-income households, the elderly, and other vulnerable segments of society. The potential exists for even larger US losses due to shifts of population and economic development to hazard-prone coastal regions, increasing population density in urban areas, and the ever-increasing interdependence of physical, social, and economic networks.

Current Practices for Resilience of the Built Environment

The resilience of communities has garnered significant attention from practitioners, researchers, and policymakers over the last decade. Earthquakes in Haiti, Chile, New Zealand, and Japan, Superstorm Sandy in 2012, and more recent hurricanes and wildfires in the United States have revealed the importance of mitigation, response, and recovery policies that focus on the resilience of the community as a whole, rather than on the safety and functionality of individual civil infrastructure facilities. Resilience assessment has become a national imperative (NRC 2012; White House 2013) not only in the United States but in Europe and countries in the Asia-Pacific Rim.

A community's resilience needs and objectives, particularly those related to postdisaster functionality and recovery, are not generally reflected in the codes, standards, and other regulatory documents that engineers typically apply in designing individual facilities for natural hazards (e.g., ASCE 2016; ICC 2018). While the performance of individual facilities (e.g., buildings, bridges, buried piping, electrical substations) and infrastructure systems (e.g., electrical, gas, and water distribution systems) during specific natural hazards is reasonably well understood, there has been less attention to the fact that such facilities and systems are interconnected and interdependent.

Natural hazards have varying temporal and spatial scales and are highly uncertain in occurrence and intensity. Similarly, while each facility and infrastructure system has its own characteristic response to a natural hazard, the performance of these systems during and after disruptive hazard events is positively correlated because of the interconnected nature of their functions in the community and the extended spatial scale of the event. These spatiotemporal correlations are not reflected in current risk and loss estimation platforms.

A New Approach to Community Resilience

In light of the numerous uncertainties associated with the performance of community infrastructure, a new risk-informed decision-making approach to community resilience assessment and enhancement is essential (Lounis and McAllister 2016). The new approach should reflect the interdisciplinary nature of the problem and the complex interdependencies among the physical, social, and economic systems in a community.

The integrated effects of physical and social infrastructure performance on the resumption of community normalcy after a hazard event and the uncertainties in recovery are depicted by figure 1 (see also Bruneau et al. 2003). Given the many dimensions of community resilience, this curve may be difficult to understand.

Furthermore, most research on community resilience in the past two decades has focused on the impacts of severe earthquakes on physical infrastructure (e.g., Bruneau et al. 2003; Koliou et al. 2018; Mieler et al. 2015). In recent years, attention has shifted to other natural hazards, including those that might be impacted by climate change (ASCE 2015).

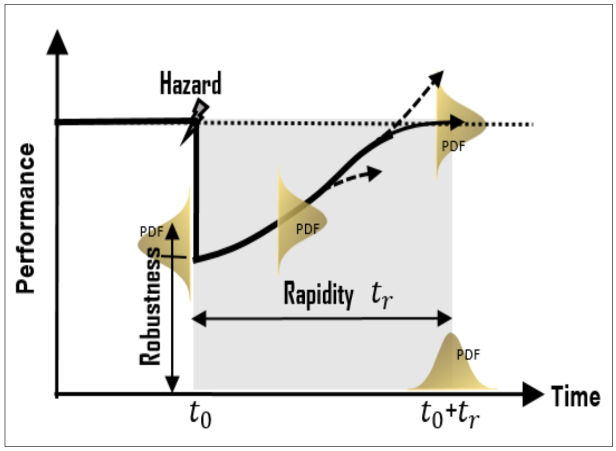

FIGURE 1 Depiction of community resilience, showing the time, t_0, at which the hazard event occurs, recovery over period t_r, and the uncertainties in damage, recovery rate, and recovery times by probability densities (PDF).

Introducing the Center for Risk-Based Community Resilience Planning

The Center for Risk-Based Community Resilience Planning (the Center; http://resilience.colostate.edu/), headquartered at Colorado State University in Fort Collins, was established as a Center of Excellence by NIST in 2015. The Center involves a dozen universities and has benefited from the participation of more than 100 investigators (faculty, graduate students, and postdoctoral fellows). Consistent with NIST research priorities, the Center's goals are to

- establish the measurement science for identifying and understanding the factors that make a community resilient,
- develop a computational environment with fully integrated supporting databases to assess the likely impacts of natural hazards on communities, and
- develop risk-informed decision support strategies with discrete sets of optimal solutions.

The Center is engaged in three major research thrusts aimed at accomplishing these goals: (1) an *I*nterdependent *N*etworked *C*ommunity *R*esilience Modeling Environment (IN-CORE) to assess alternative strategies for improving community resilience; (2) a standard data ontology, robust architecture, and management tools that support IN-CORE; and (3) testbeds, hindcasts, and field studies to validate the advanced modeling environment.

Community Resilience Measurement Science: Overview of the Center's Programs

NIST and the Center define communities as regional entities with a common governance structure that allows coordinated decision making and policy implementation. The Center's research takes a broadly integrated and interdisciplinary approach toward modeling natural hazards, interdependent physical infrastructure systems, and social and economic institutions that are supported by the built environment. The natural hazard models include hurricanes/storm surge/coastal inundation, earthquakes, and riverine flooding, as well as hazards that may be more localized and less well defined for engineering analysis, such as tornadoes, tsunamis, and wildland-urban-interface fires.

To lay the groundwork for advances in community resilience science, research at the Center is addressing

- single, multiple, and cascading hazards, modeled as scenarios at the community scale;
- the performance of physical components and systems—buildings, transportation networks, water and wastewater systems, energy networks, telecommunication networks, and their geospatial and logical interdependencies;
- economic modeling using computable general equilibrium (CGE) models;
- social systems and cascading effects, including event impacts and recovery;
- optimization strategies for enhancing the selection of community resilience strategies that consider uncertainties in natural hazard occurrence, intensity, and physical-socioeconomic response;
- exploratory testbeds, full validation of the modeling environment using hindcasts, and field studies of communities of differing sizes;

TABLE 1 Examples of community performance goals and resilience metrics

Community performance goals	Examples of resilience metrics
Population stability	Number of households dislocated; percent of population remaining in the community; percent of population remaining in homes; change in housing vacancy rate
Economic stability	Household income; employment; earnings by sector; assessed value of property; change in taxes and revenue (resources); change in gross city product (GCP)
Social services stability	Hospital bed demand/supply ratio; school teacher/student ratio; availability of key retail and financial services
Physical services stability	Percent functionality of buildings and transportation systems; percent of population served by water, wastewater, electric power, gas, and telecommunication systems
Governance stability	Percent of population with access to police and fire protection and essential public government services

- a resilience data management structure and a community resilience glossary and taxonomy; and
- standard tools and protocols for longitudinal post-event community surveys.

A measurement science–based approach to community resilience assessment and decision making also requires community goals, or aspirational statements, quantified by resilience metrics to determine whether the goals have been achieved. The Center, in collaboration with NIST research staff, has developed tentative community resilience goals and metrics (table 1) informed by the *NIST Community Resilience Planning Guide* (NIST 2016).

The Interdependent Networked Community Resilience Modeling Environment (IN-CORE)

IN-CORE provides the structure and direction to the Center's research programs and is one of the Center's most notable accomplishments to date (Gardoni et al. 2018; van de Lindt et al. 2018a).

Built on the recognition that the resilience of a community depends on interconnected physical, social, and economic systems, IN-CORE provides novel and comprehensive modeling to enhance understanding of the decision points, actions, and resources that communities use to improve their resilience. It is being developed as an open-source research tool that integrates estimates of the impacts of natural hazards on the built environment to support collaborative research by experts in community resilience modeling and assessment. It is also intended to inform users about the (a) potential impacts of natural hazard events on communities, (b) effectiveness of policy and project decisions aimed at enhancing community resilience, and (c) development of best practices for achieving community resilience.

The structure of IN-CORE is illustrated in figure 2. Some modules are core modules while others may be user supplied, facilitating use as a research tool. Modules must be called in a specific order, a requirement necessitated by the input and output for information flow and integration. Users can enter and exit the workflow at any point, depending on their analysis needs.

IN-CORE can simulate the effects of various strategies for improving community resilience (e.g., reduced times to restore functionality; Zhang et al. 2017). Feasible or optimal strategies for providing risk-informed decision support can also be identified using algorithms based on one or more hazard scenarios, as indicated in figure 3, which shows the results of a multiobjective optimization analysis aimed at minimizing cost and household dislocation (Zhang and Nicholson 2016).

The decision framework is not intended to endorse specific resilience improvement strategies; these involve local social, economic, political, and cultural values that require community consensus. Rather, it is intended to provide choices that improve community resilience related to physical and socioeconomic systems and the availability of services (e.g., health care).

Exploratory Testbeds, Hindcasts, and Longitudinal Field Studies for Architecture Validation

The fundamental measurement science (e.g., methods and metrics to quantify resilience) and the IN-CORE computational environment have been developed through testbeds, hindcasts, and field studies involving interdisciplinary teams of engineers, social and economic scientists, and information technologists.

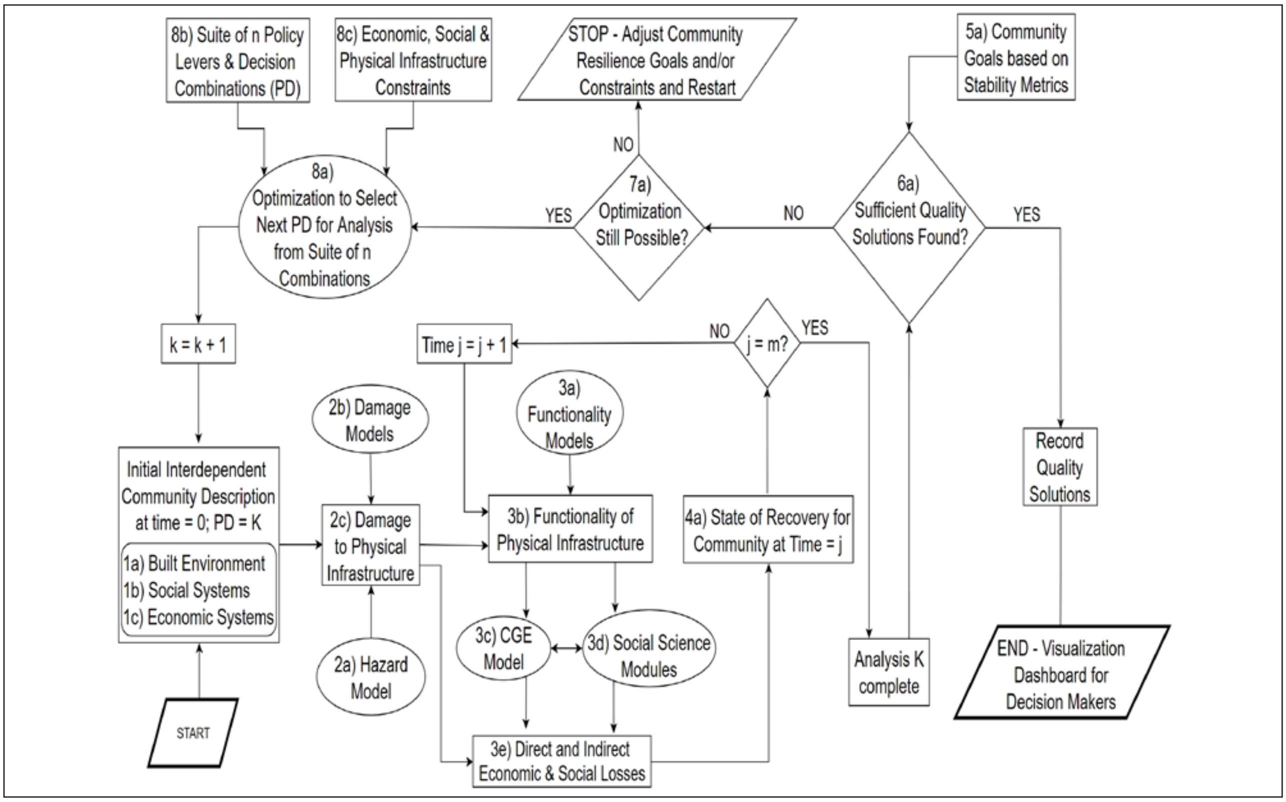

FIGURE 2 Basic conceptual structure of IN-CORE. CGE = computable general equilibrium; j = time; K, k = numbers assigned to PD considered; m = total number of time steps considered in modeling the community; PD = policy description.

The Center took this approach for three primary reasons: to require interdisciplinary collaborations, which seldom happened in the past; to advance integrated temporal (longitudinal) and spatial (regional) modeling of community recovery; and to ensure that the supporting research and development are relevant to real communities. Each study was created for a specific purpose.

The *Centerville Virtual Community Testbed* is an idealized community of 50,000 residents with an economy, infrastructure, and demographics intended to be representative of similarly sized communities exposed to seismic hazards in the central United States. It provides a platform suitable for interdisciplinary team training (Ellingwood et al. 2016).

The *Seaside, OR Testbed* involves a small coastal resort community that is being used as a model to develop multihazard damage and loss assessments for earthquake and tsunami scenarios originating from the Cascadia Subduction Zone (Attary et al. 2017). Impacts considered include population dislocation as a result of structural damage to buildings as well as loss of building functionality due to lack of potable water, and

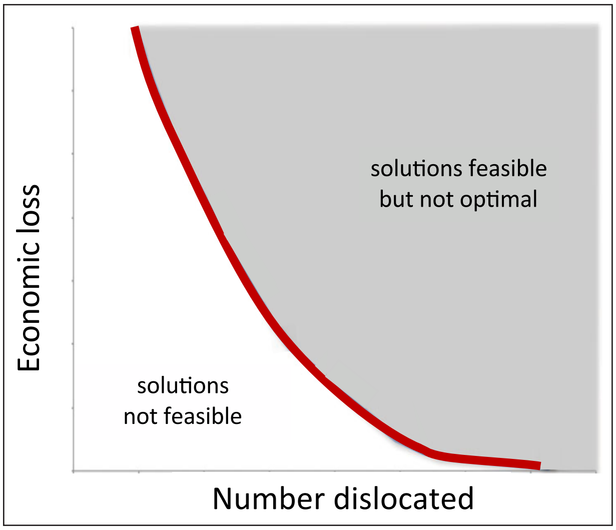

FIGURE 3 Conceptual representation of multiobjective optimization. The number of dislocated and economic losses cannot be minimized at the same time and are competing objectives. The heavy red line, referred to as a Pareto surface, describes a trade-off in optimal decisions that depend on the values of the decision maker. A decision maker will choose a point in the upper left region of the curve if the concern is primarily with social impact, and a point in the lower right if the concern is with economic losses.

temporal reduction in water demand due to population dislocation (Guidotti et al. 2017).

The *Galveston and Bolivar Peninsula, TX Testbed* integrates models that include the effects of hurricane wind and storm surge and performance of interdependent physical infrastructure systems on housing and business disruption and population dislocation. Postevent housing recovery modeling is being advanced using empirical findings from Hurricane Ike in 2008. Factors that affect housing recovery include resource availability, social capacity, business continuity, infrastructure system performance, and access (Hamideh et al. 2018).

The *Metropolitan Memphis Statistical Area Testbed* involves a nine-county region of approximately 1.4 million people exposed to earthquake and flood hazards and is the largest testbed in the Center. The inclusion of surrounding counties allows examination of the impact of support from adjacent communities on resilience and the degree to which algorithms developed on smaller testbeds can be scaled to an urban area. A CGE model of eight employment and residential areas subject to varying effects was developed as part of this testbed.

Risk-informed decisions take into account event likelihood, consequences, and contextual factors to enhance community resilience planning.

The *Joplin, MO Hindcast* was designed to validate the accuracy of IN-CORE modeling of both individual physical sectors and coupled physical, social, and economic sectors in responding to the twin-vortex EF-5 tornado of May 22, 2011. The Center's tornado and fragility models were applied to a series of analyses, from spatial building damage analysis (compared to building inspection data after the event) to population dislocation data (compared to data collected both immediately after the event and during Joplin's path to recovery) (Attary et al. 2018).

Finally, the *Lumberton, NC Longitudinal Field Study* is an example of synergies achieved by collaboration between NIST and the Center. After Hurricane Matthew caused severe flood damage in Lumberton in September 2016, a Center-NIST team visited to assess building damage, survey a representative sample of households to document their dislocation and early recovery efforts, and meet with community leaders, infrastructure stakeholders, and public officials to discuss overall impacts and recovery decisions and issues. Figure 4 shows estimated days of dislocation for sampled Lumberton housing/households.

The team returned to Lumberton in early 2018 to follow up on recovery and to initiate a survey of business recovery, and has plans to return periodically to measure recovery progress. Such longitudinal studies, where observations are collected over time for the same cases (e.g., buildings, households, organizations), enhance understanding of interdependency challenges in hazard recovery and community resilience. This in turn supports efforts to quantify correlations between population dislocation and race/ethnicity, income, and education level, and thus inform recovery modeling in the IN-CORE computational environment (van de Lindt et al. 2018b).

Community Resilience Challenges

Challenges to community resilience assessment are numerous and vary among members of the resilience community. The following are generally recognized as common challenges.

Verification and Validation

The IN-CORE computational environment integrates engineering, social science, and economic models, and their coupling raises a number of practical difficulties. Among them, engineering and social science models are typically of different scales (e.g., region, parcel, neighborhood, buildings); and while engineering models are based on laws of physical science or mechanics, social science models are highly data driven. These differing models must communicate with each other within and across IN-CORE modules.

Because investments in community resilience and risk mitigation may be significant and must be amortized over decades, confidence in IN-CORE's ability to capture the likely performance of physical and social infrastructure with reasonable accuracy is essential. Verification and validation are a multifaceted process that involves testing the individual modules in figure 2 and their linkages, and comparing predictions with data from hindcasts and field studies.

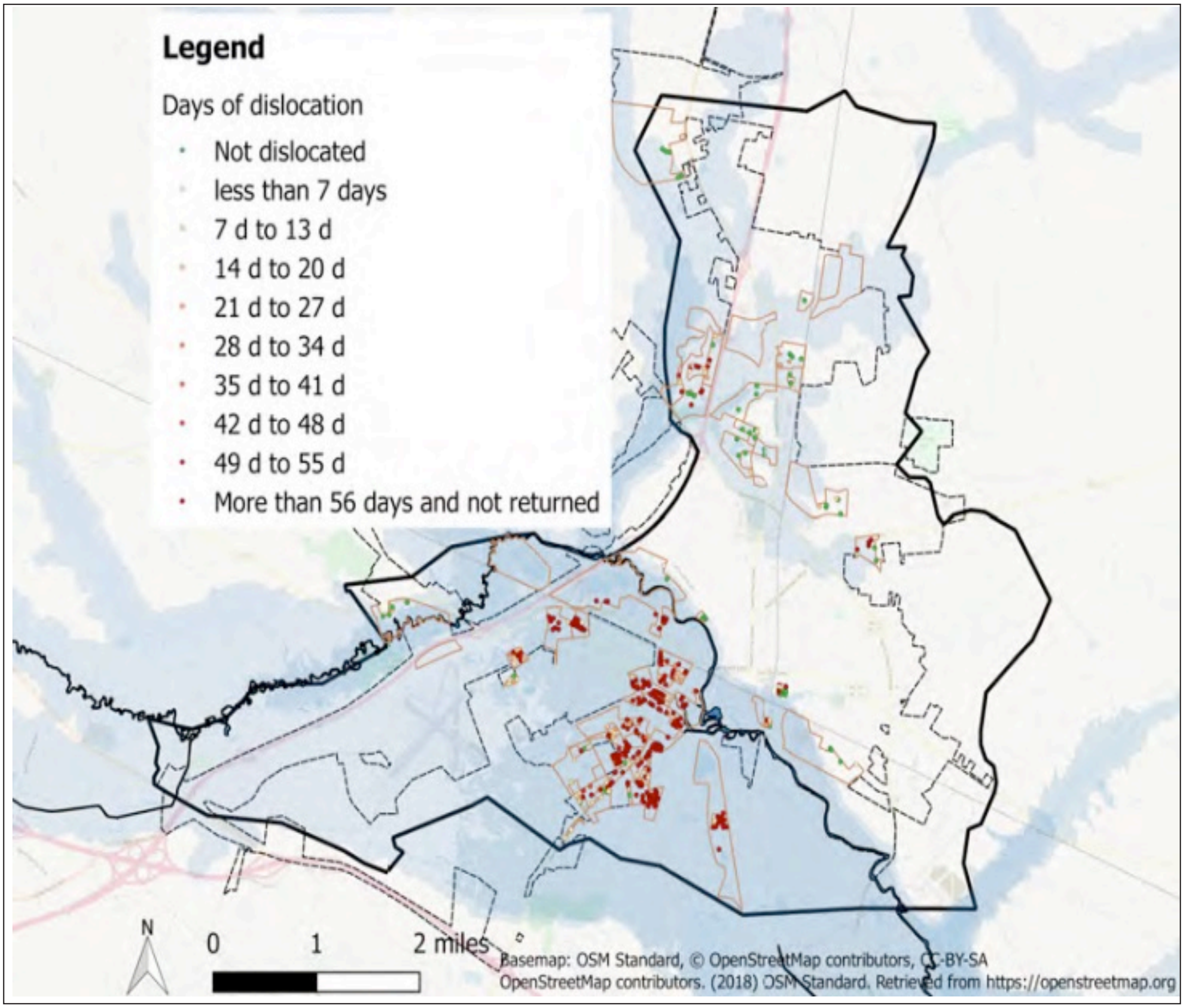

FIGURE 4 Estimated days of dislocation for sampled Lumberton, NC housing/households. Source: van de Lindt et al. (2018b).

Financing Community Recovery and Resilience

How will communities pay for resilience improvements and recovery? This question is difficult to address.

Disaster response and recovery are financed mainly by the federal government (e.g., the Federal Emergency Management Agency, Housing and Urban Development, Small Business Administration), nonprofits, and insurance. These programs may be *reactive*, in that they generally are not mobilized until after a disaster has occurred, or they may support *proactive* measures before a natural hazard event. Community resilience planning to reduce risk can be improved significantly with proactive measures. New opportunities for proactive resilience planning and implementation were addressed by the Disaster Recovery Reform Act of 2018 (Ellard et al. 2018).

Financing to enhance community resilience typically requires a variety of funding sources in the public and private sectors. Little consideration has been given to drawing on the capital markets, although the funds potentially available overshadow resources from government programs or the insurance industry (Goda 2015).

Risk Analysis and Risk-Informed Decision Support

The risk-informed decision process is poorly understood for community resilience planning with integrated physical, social, and economic models. IN-CORE will facilitate risk-informed decisions that take into account likelihoods and consequences of natural hazard events. Risk attitudes of decision makers also vary by context; the risk tolerance of communities whose inhabitants have been exposed to a prior disruptive event may be different from that of inhabitants who have not.

In addition, the manner in which risk is communicated from the results of the IN-CORE analysis is at least as important as the manner in which it is assessed technically (NRC 1989); risk goals must be adaptable to individual communities. A typical community resilience goal and metric might read: "The population stability goal will be met if 95% of the population can resume residency four weeks after event H with 90% confidence."

Finally, existing decision methods to support community resilience goals require modifications to achieve sustainable long-term decisions for enhancing community resilience, when the investment horizon extends to 50–100 years or more.

Best Practices for Community Resilience

Community resilience assessment and enhancement may require a variety of measures, such as

- improved codes and standards that meet resilience goals for community buildings, bridges, and other infrastructure and are consistent with current engineering practice (Ellingwood et al. 2019; Lin et al. 2016);
- land use policies;
- incentives such as tax credits and discounts on insurance for individual homeowners and businesses to enhance the resilience of their properties; and
- educational programs for property owners and future resilience practitioners on methods of resilience enhancement.

Meeting community resilience goals often involves an economic analysis component to understand the cost of policy decisions. Questions of whether up-front costs are justified by future risks and who pays the costs and who receives the benefits drive the debate in most communities.

Conclusion

Modern communities consist of closely integrated civil infrastructure systems and social and economic institutions that are essential for the health and welfare of their inhabitants. The Center's overarching goals are to establish the measurement science for identifying and understanding the factors that make a community resilient, to develop a computational environment with fully integrated supporting databases to assess the likely impact of natural hazards on communities, and to develop risk-informed decision support strategies for optimal solutions. These goals are supported by collaborative field studies and research to improve IN-CORE and its supporting databases.

Readers interested in learning more are encouraged to visit the Center's website,[1] which includes a list of Center publications and yearly webinars hosted for the resilience community.

Acknowledgments and Disclaimer

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Resilience efforts in Los Angeles can provide insights for connecting scientific and engineering research to policies for stronger, safer, and more resilient communities.

Resilience by Design

Lucile Jones

Marissa Aho

Lucile M. Jones and Marissa Aho

Los Angeles, the second largest city in the nation and home to the largest US port, is subject to some of the greatest risks from natural disasters. It is situated among the eight counties of Southern California where more than 150 fault segments are each capable of generating a damaging earthquake (Shaw et al. 2015) in an area with more than 23 million residents (figure 1). The economy of Los Angeles and Orange Counties has a GDP over $1 trillion (BEA 2018), and the region comprises geographically and politically defined cities and municipalities linked by interdependent economies, shared natural resources, and integrated transportation systems. A large earthquake that affects the city of Los Angeles also impacts the surrounding counties and has serious economic consequences and unforeseeable effects for the state of California and the nation.

Overview

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). A Federal Emergency Management Agency (FEMA) analysis of expected losses from future earthquakes predicts an annual average

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of more than $2 billion per year in the eight counties of Southern California, with half of those losses in Los Angeles County alone (FEMA 2017; Petersen et al. 2014). Furthermore, wildfires, debris flows, and floods are also major risk factors for the region.

Recently, the City of Los Angeles has moved aggressively in a new direction to understand and address risk and vulnerability and to increase resilience. It entered a technical assistance agreement with the US Geological Survey (USGS) to use the science developed about the probable consequences of future earthquakes to create a long-term plan to improve seismic resilience.

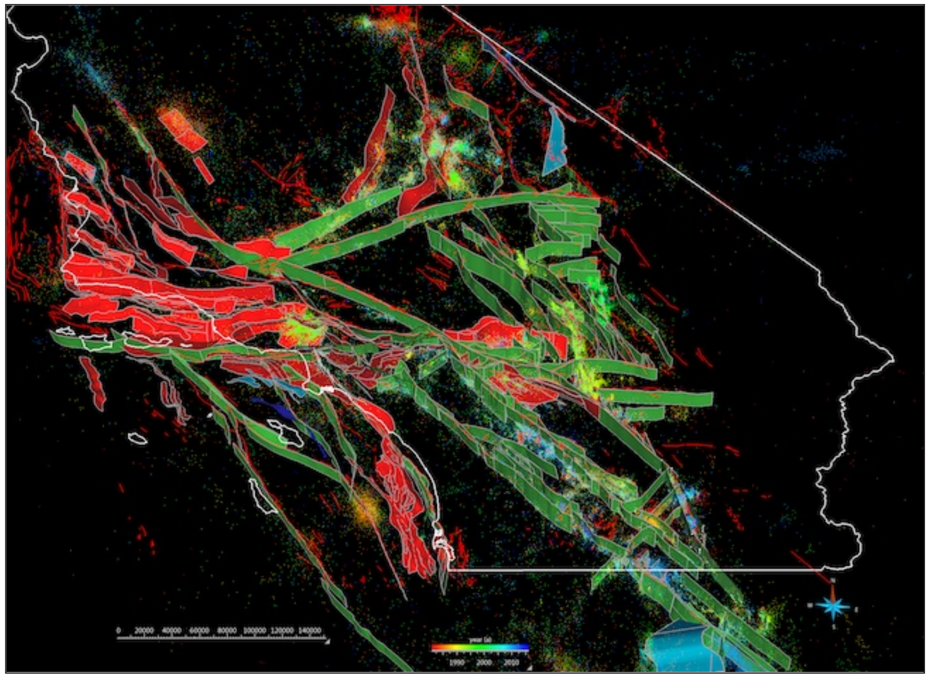


FIGURE 1 Visualization of the Southern California Earthquake Center Community Fault Map 5.1. The colored strips denote the types of faults that proliferate throughout the region. Small colored dots denote the epicenters of earthquakes recorded by the Southern California Seismic Network from 1981 to 2014. Reprinted with permission from Shaw et al. (2015).

A team of senior staff in the mayor's office worked 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 losses. From this, Mayor Eric Garcetti proposed 18 actions to increase the city's seismic resilience—through ordinances (by the city council), executive action, and partnership activities—in a report titled *Resilience by Design*.[1] Implementation is directed by the mayor's office, with the appointment of the second author (MA) as the city's first chief resilience officer, a position originally funded through a partnership with 100 Resilient Cities,[2] pioneered by the Rockefeller Foundation and now institutionalized in the mayor's office.

The resilience efforts of the City of Los Angeles have expanded beyond seismic objectives to address climate change, aging infrastructure, and economic insecurity–driven shocks and stresses. This successful effort required the integration of science and policy and can provide some insights for communities that want to better connect scientific and engineering research to policies for stronger, safer, and more resilient communities.

[1] http://lamayor.org/earthquakes

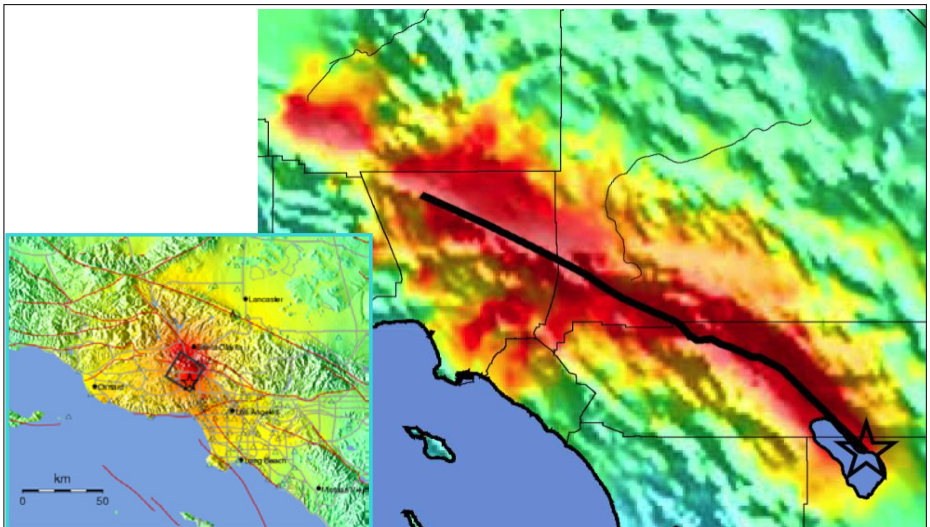
[2] https://www.100resilientcities.org/

Background

The assessment of the severity of the earthquake risk for Los Angeles relied on a USGS report, *The ShakeOut Scenario* (Jones et al. 2008), which details the consequences of a plausible magnitude 7.8 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). Earthquakes on faults closer to the city will cause more intense damage in parts of Los Angeles, but the very likely earthquake explored in the report happens over a larger area and strains regional capabilities through the scale of the damage. The *ShakeOut* model predicts effects of a modified Mercalli intensity IX[3] over thousands of square kilometers and strong shaking lasting several tens of seconds (figure 2), causing about 1,800 deaths and $213 billion in economic losses across Southern California (Jones et al. 2008).

Earthquakes actually pose a much smaller risk to human life than many other risks in Southern California;

[3] The Mercalli scale (I–XII) measures the effects of an earthquake quantified from observations of effects on buildings, people, objects, and the Earth's surface, while the Richter scale (2.0–10.0) uses a seismograph to measure the energy released by an earthquake.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

FIGURE 2 ShakeMaps of the instrumental intensity of earthquake shaking in the 1994 magnitude 6.7 Northridge earthquake (*left*; from USGS), and (*right*) predicted for a magnitude 7.8 earthquake on the southern San Andreas fault, at the same scale. The star denotes the hypothesized epicenter at the southern end of the San Andreas fault. Source: Jones et al. (2008).

those 1,800 fatalities, which will occur only once every few hundred years, are fewer than the number of people who will die in traffic accidents in Los Angeles County over 7 years (LA County Department of Public Health 2011). However, the relative risk that earthquakes pose to individual and collective pocketbooks is much greater. In LA County, the expected annualized loss from all earthquakes is over $1.5 billion, representing one quarter of the total direct loss from earthquakes facing the nation (FEMA 2017). For reference, the $213 billion in losses in the *ShakeOut* earthquake equals the cost of physical damage in about 60 million car crashes (III 2019) or 60 years of accidents in LA County (OTS 2019).

Resilience by Design

The City of Los Angeles and US Geological Survey (USGS) created a formal partnership to provide scientific advice to the city as it created a plan to address its seismic vulnerability; as part of this partnership the first author (LMJ), a seismologist with the USGS, spent a year in the mayor's office.

Goals

Recognizing that addressing every possible seismic vulnerability would be too large a task, the project focused on four primary goals:

- Protect the lives of 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.

The results of the *ShakeOut Scenario* were used to identify the following areas that could be addressed through city policies and would have the greatest impact on those four goals:

- pre-1980 nonductile reinforced concrete buildings,
- pre-1980 soft-first-story buildings (i.e., those with windows, wide doors, and large open areas),
- water system infrastructure, including impact on firefighting capability, and
- telecommunications infrastructure.

Collaboration and Stakeholder Engagement

The creation of this plan for seismic resilience was the result of a year-long collaboration among policymakers, technical experts, and community stakeholders. The policymakers were primarily senior staff from all divisions of the mayor's office, while the USGS brought in relevant technical experts.

To address dangers from vulnerable buildings, a mayor's Seismic Safety Task Force was convened that included leaders of the state's practicing and academic structural engineering community and engineers from the LA Department of Building and Safety. They evaluated which types of buildings pose the greatest risk and approaches to fix the problems, and then drafted proposed ordinances for consideration by the city council. Technical issues for the water system were addressed by a team of LA Department of Water and Power employees with expertise in the various water system components. Telecommunication aspects were considered by representatives of four cellular providers. In addition to these three task forces, many outside experts were engaged to address particular areas of concern.

Much of the year's work involved meeting with stakeholders in Los Angeles's future—elected and city department officials, building owners, business leaders, real estate managers, civic leaders, and representatives of community organizations—and helping them both understand the ramifications of possible recommendations and compare expected losses with mitigation costs. Over 130 meetings were held in the 10 months from early February 2014 to the release of the report December 8, 2014. Most of the meetings involved a presentation about the science of the seismic risk and economic consequences, time for questions, discussion of possible approaches to address the risk, and solicitation of ideas for new approaches. The primary focus of the discussions was the potential for economic disruption.

Recommendations

The recommendations for buildings, water, and telecommunications were developed in parallel to address overlap. There is a strong interdependence of systems in a complex modern urban environment—the loss of water infrastructure would disrupt a large part of the economy, or damage to one building would reduce the value of others through blight or the cordoning off of adjacent properties. It makes no sense to spend a lot of money fixing buildings if there will be no water to allow occupancy after the earthquake. The focus was on increasing the resilience of the potentially fragile regional economy.

The resulting recommendations (table 1) were published in 2014 by the mayor's office. Those that required ordinances from the city council were all passed unanimously in October 2015.

Resilient Los Angeles 2015–2018

Implementation of the recommendations in *Resilience by Design* began in 2015. As a former urban planner and the city's first chief resilience officer, the second author (MA) was charged with leading the development of a comprehensive resilience strategy for the city.

Specific Implementation

In 2015 and 2016 the following five ordinances stemming from the recommendations were supported and approved by the city council and signed by Mayor Garcetti. The legislative process required strong support from the telecom industry, apartment associations, tenant organizations, and the engineering and construction community.

- May 2015: Stronger telecommunications standards for all new cellular towers became law (Ordinance 183580). As of early 2019, dozens of new cellular towers had been constructed with an importance factor of 1.5 instead of 1.0.
- October 2015: Mandatory retrofits for pre-1980 nonductile reinforced concrete buildings became law (Ordinance 183891). As of early 2019, more than 1,300 nonductile reinforced concrete buildings had received orders to comply from the Department of Building and Safety (LADBS) and 160 of these buildings had submitted the initial checklist to begin the process. As of March 2019, it was determined that 20 buildings had been previously retrofitted; none have yet completed a new retrofit under this program. These buildings have 25 years (until 2043) to complete the retrofits.

Recommendations for buildings, water, and telecommunications were developed in parallel to address overlap and focus on financial outcomes.

- October 2015: Mandatory retrofits for pre-1980 soft-first-story buildings became law (Ordinance 183891). As of early 2019, more than 13,000 such buildings had received LADBS orders to comply. More than 7,800 of these buildings have formally begun the 3-step process to complete the retrofits, and 1,500 buildings have completed retrofitting, representing 21,000 households that are safer today.
- February 2016: A cost-sharing agreement that had been heavily debated with tenant rights organiza-

TABLE 1 Recommendations for seismic resilience from *Resilience by Design* (http://lamayor.org/earthquakes)

1. Strengthen buildings	2. Fortify the 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 and Water Departments will develop a resilient and alternative water system for firefighting 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 before enactment of the 1976 Uniform Building Code meet the Basic Safety Objective in ASCE 41.	(b) Identify mitigation alternatives for the Los Angeles Aqueduct across 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 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 (LADWP), California Metropolitan Water District, and Department of Water Resources, to create a collaborative and regional approach to protecting the resilience of the water supply.	(c) Create a Southern California Utility Resilience Task Force to develop solutions for potential cascading failures in 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 LADWP 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, using the system designed by the US Resiliency Council.	(e) Actively pursue the 2010 Urban Water Management Plan to develop local water supplies through storm water capture, water conservation, and water recycling.	(e) The City of Los Angeles and the USGS will begin to implement early earthquake warning (EEW) 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 LADWP, to promote seismic resilience as a core function of LADWP.	
	(h) Work with local, regional, and state partners to develop a seismic resilience bond measure to allow investment in the seismic safety of the region.	

tions and apartment owner associations became law (Ordinance 184080). The ordinance limits the proportion of costs related to the mandatory seismic retrofitting to allow building owners to pass through up to 50 percent of the total cost of the work required, up to $38 per month for each tenant.

- March 2016: A mandatory evaluation and retrofit of buildings that experienced substantial damage at lower levels of shaking became law (Ordinance 184169). As of early 2019, the City of Los Angeles has not experienced a seismic event that has triggered any buildings to be evaluated or retrofitted.

Earthquake Early Warning

One of the *Resilience by Design* recommendations was to implement earthquake early warning (EEW) in Southern California. The City of Los Angeles had begun beta testing such a system in 2012, and in April 2017 Mayor Garcetti announced that earthquake early warning would be effective for Angelenos by the end of 2018.

The mayor's office worked closely with USGS, first through a technical assistance agreement and then through two pilot agreements. The latter were for use of the signal from the new ShakeAlert system (www.ShakeAlert.org; Given et al. 2018) to (a) develop, test, and pilot an EEW app with city employees and (b) link EEW to the public address system at LA City Hall. On October 18, 2018, during the Great ShakeOut, LA City Hall became the first public building with earthquake early warning. And, as promised, on December 31, 2018, the ShakeAlertLA EEW app was uploaded to Apple and Android stores in English and Spanish. As of May 2019, more than 470,000 cellular devices had downloaded the ShakeAlertLA app.

Beyond Earthquakes

In 2016 and 2017 the mayor's office worked with 100 Resilient Cities and hundreds of subject matter experts to expand the city's approach to resilience to other serious shocks and stresses. Partners included the UCLA Institute of the Environment and Sustainability, looking at urban heat islands and extreme heat risk and vulnerability; and USC Sea Grant and USGS Coastal Storm Modeling System (CoSMoS), looking at sea level rise and tsunami risk and vulnerability.

Using the momentum gained by implementation of *Resilience by Design*, additional recommendations were identified and in March 2018 Mayor Garcetti released *Resilient Los Angeles*,[4] a comprehensive citywide resilience strategy with 15 goals, 96 actions, and 25 targets for Angelenos, neighborhoods, the city, and regional partners. He also signed an executive directive requiring the leaders of all city departments and commissions to implement the recommendations and to include resilience principles both in their strategic plans and in the development of department budgets. In addition, nearly 30 departmental chief resilience officers were appointed, from LA World Airports to the LA Zoo, to coordinate the city's multidisciplinary approach to resilience building.

Meanwhile, the implementation of *Resilience by Design* recommendations continued. The mayor's office worked with Craig Davis, resilience manager for water at the LADWP, to advance many of the recommendations to fortify the water system. Postearthquake fire risk was researched and mapped, a panel was formed to partner with external subject matter experts, and a task force was formed by the LADWP, Metropolitan Water District, and Department of Water Resources (see Davis and Shamma 2019 in this issue). And within approximately 3 years, a pilot to install 2 miles of earthquake-resistant ductile iron pipes became a plan to install a citywide seismic-resilient pipe network that will ensure delivery of water to Angelenos after an earthquake.

Lessons Learned

There are important lessons learned. First, even as policymakers and scientists worked in close collaboration, it was important to recognize their fundamentally different roles. Scientists can give policymakers a prediction of the probable consequences of their decisions. As citizens and voters, they probably have an opinion as to the appropriate policy to respond to that information, but that is not part of the science. Policymakers are elected to determine policy. This distinction is important for two reasons. First, if scientists start making policy, politicians might be invited to start making science. Second, policymakers fight for the policies they have made, so empowering them to make more informed decisions creates more forceful advocates who actually have the power to get something done.

Empowering policymakers to make more informed decisions creates more forceful advocates who actually have the power to get something done.

Second, it was important in bringing science and engineering to the decision makers to stay focused on what is known rather than on the uncertainties. Scientists and engineers know that uncertainties matter and are integral to the scientific endeavor. Policymakers need answers and rely on hearing a consensus from scientists. Results are most effective when (a) it can be demonstrated that they are the consensus of the scientific and engineering community and (b) they are presented as such, not the process by which they were achieved.

Third, people support something they help to create, so engaging stakeholders in the discussion from the

[4] https://www.lamayor.org/Resilience

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 could have become significant barriers to its enactment. Being able to affect some part 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 scientists and engineers. This collaboration is the culmination of decades of interactions, especially those that developed during the *ShakeOut Scenario* process. For the past 7 years, 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 as well as the relationship with the scientists and engineers. People listen to those they trust, and that trust comes from familiarity and shared experience.

People support something they help to create, so engaging stakeholders from the beginning is a condition for success.

Fifth, *Resilience by Design* intentionally set a limit, in both time and scope, to help prioritize the most critical challenges. Discussion of risks and vulnerabilities can sometimes be overwhelming to policymakers who may focus on day-to-day challenges. We intentionally did not address all earthquake problems, and we prioritized solutions that helped address other problems as well. For instance, we found that one of the most compelling ways to discuss the importance of soft-story retrofits was to remind officials that approximately half a million Angelenos were living in these vulnerable buildings. At a time when addressing the crisis in affordable housing and homelessness is a high priority in Los Angeles, reducing the risk of losing these buildings in an earthquake has multiple benefits.

Looking Forward

One of the biggest difficulties in building a resilient community is that success is defined by what does *not* happen, a phenomenon that to some extent must be considered impossible to measure. It is difficult for nonspecialists to understand that the lack of damage is because of their actions and not just because this earthquake wasn't that bad. Success is also a form of delayed gratification; the consequences may be seen only decades after the action taken. The long delays and somewhat hidden results (a successful retrofit should not look different) make building social momentum a challenge.

It is thus particularly gratifying that the current effort by Los Angeles seems to be playing out in ripple effects across the region. Since Los Angeles passed the retrofit ordinance in October 2015, similar ordinances have been passed in five other Southern California cities and are under consideration in several more. Both authors continued engaging with other regional cities after the release of *Resilience by Design* to support further action. Two cities (Santa Monica and West Hollywood) went beyond Los Angeles and included mandatory retrofit of pre-1994 welded steel moment-frame buildings.

All of these programs have been adopted without the occurrence of a significant local earthquake. It will be interesting to see how many more communities might join the effort after the next damaging earthquake. One might expect that the increase in action may depend on the degree to which the retrofitting ordinances will appear to have been successful.

Acknowledgments

The collaboration described in this paper was the work of an untold number of people at all levels in Southern California, made possible by the leadership of Mayor Eric Garcetti. Describing the work is an endeavor made easier by the great editing of Cameron Fletcher.

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The nation's largest state, regional, and municipal water agencies are working together to enhance the seismic resilience of Southern California's water supply.

Improving the Resilience of Southern California Water Supply Aqueduct Systems to Regional Earthquake Threats

Craig A. Davis and
John E. Shamma

Craig Davis

John Shamma

Southern California is home to over 19 million residents who rely on three independently owned and operated aqueduct systems that provide on average 50 percent of the region's annual water needs. The three aqueducts import water from outside the region and cross the San Andreas Fault. The potential loss of all three aqueducts in a single major San Andreas earthquake event poses a serious threat to Southern California and the United States economy.

In response to this threat, a multiagency Seismic Resilience Water Supply Task Force was created to examine assumptions regarding earthquake-induced damage, review likely repair durations for the aqueduct systems, and develop a coordinated approach to restore water supplies to the region if an earthquake event compromises one or more of the aqueducts.

The Southern California Aqueduct Systems

The three aqueduct systems that import water to Southern California are the California Aqueduct as part of the State Water Project (SWP), Colorado River Aqueduct (CRA), and Los Angeles Aqueduct (LAA) (figure 1).

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The independently owned and operated systems work in conjunction to supplement local water resources and meet the demands of the region. The overlapping of the supply operational areas provides an opportunity for the responsible agencies to coordinate their efforts should any of the aqueducts become damaged from a seismic (or other) event.

The California Department of Water Resources (DWR) operates the SWP, the nation's largest state-built water development and conveyance system. Placed into service in the early 1970s, the SWP provides water for 25 million residents, farms, and businesses statewide, including 19 million people in the Southern California urban area (figure 1) via the California Aqueduct's East and West Branches. The water is purchased and distributed by various state water contractors; the Metropolitan Water District of Southern California (MWD) is one of these contractors.

MWD is the nation's largest wholesale water agency and owns/operates the CRA, which was constructed in the 1930s to import water from the Colorado River to Southern California. MWD also owns and operates five water treatment plants and over 800 miles of pipeline to distribute water imported from the CRA or the SWP California Aqueduct East and West Branches to member agencies. Additionally, an interconnection between the LAA and MWD system can be used to supplement the portion of MWD's service area that is normally supplied by the SWP West Branch with water from the LAA.

The Los Angeles Department of Water and Power (LADWP, an MWD member agency) is the nation's largest municipal water agency and the owner/operator of the LAA system, which was constructed in the early 1900s and expanded in the late 1960s to import water from the Owens River in the Eastern Sierra Nevada. The LADWP and the area supplied by the LAA can also be supplied by SWP and CRA water.

FIGURE 1 Major aqueduct systems that import water to Southern California. The legend identifies each aqueduct, the San Andreas Fault, and the Southern California urban area. All three systems, which provide water to the Los Angeles and San Diego urban area, cross the San Andreas Fault (red line).

The San Andreas Fault

As seen in figure 1, the three aqueducts cross the San Andreas Fault (SAF), which runs nearly the entire length of California.[1] It is primarily a strike-slip fault moving with right-lateral motion; however, there is a compressional portion in the vicinity of San Gorgonio Pass (about 90 miles east of Los Angeles) where the fault would be expected to have significant uplift (Weldon et al. 2016), which could be especially disruptive to the flow of water through aqueducts.

[1] The fault is about 1,200 km (750 miles) long and runs from just west of Eureka in the north to the Salton Sea (about 150 km, or 90 miles, east of San Diego) in the south, marking the tectonic boundary between the American and Pacific plates.

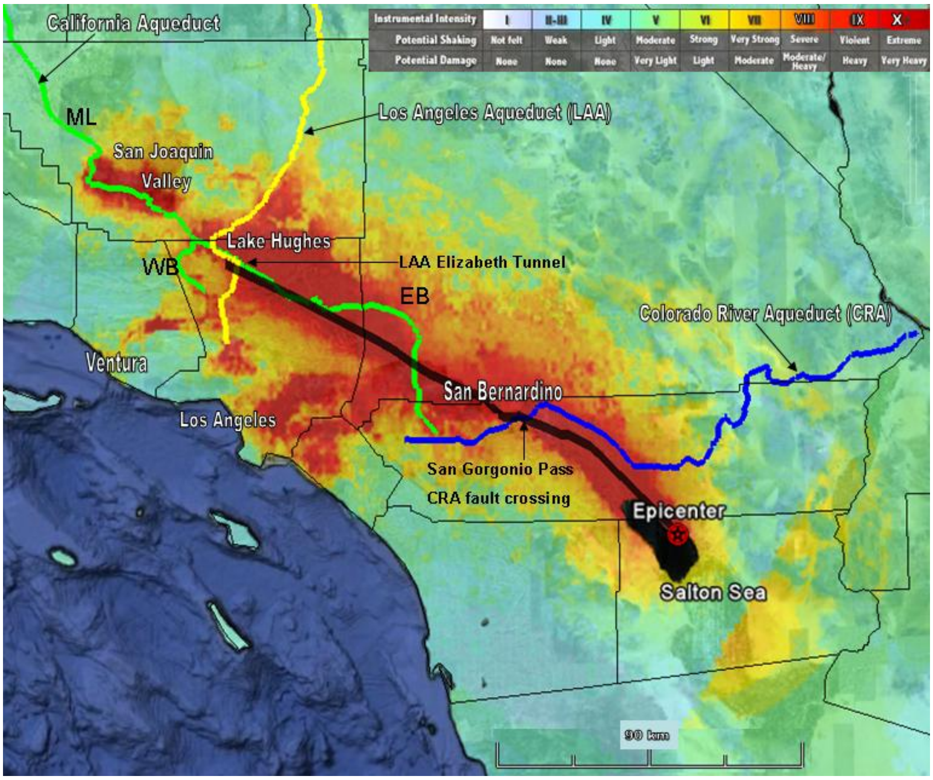

FIGURE 2 Southern California region showing the *ShakeOut Scenario* epicenter (star), fault rupture (heavy black line), and shaking intensity. CRA = Colorado River Aqueduct (blue line); EB = East Branch of the California Aqueduct; LAA = Los Angeles Aqueduct (yellow line); ML = Main Line of the California Aqueduct (green line); WB = West Branch of the California Aqueduct. Reprinted from Davis and O'Rourke (2011) by permission from the Earthquake Engineering Research Institute.

The SAF has produced earthquakes of moment magnitude (M_w) 7.8–7.9 (in 1857 and 1906). Major earthquakes of M_w 7.25 or larger on the southern SAF occur every 100–150 years (Scharer et al. 2017). It has been over 150 years since the last earthquake ruptured across locations of the SWP and LAA and over 300 years since the last rupture crossed the CRA location (Philibosian et al. 2011; Scharer et al. 2010).

Assessment of the Threat: The ShakeOut Scenario

In 2008 the US Geological Survey, along with many partners, completed a study of a plausible M_w 7.8 earthquake on the southern SAF (Jones et al. 2008) for use in the Great Southern California ShakeOut exercise (hereafter, the *ShakeOut Scenario*). Figure 2 shows the region, ruptured portion of the SAF (black), shaking intensity for this scenario, and how it affects the broad Southern California urban area (figure 1). The hypothesized M_w 7.8 earthquake has an epicenter at the Salton Sea and ruptures along a 300 km (190 mile) distance north to Lake Hughes (Graves et al. 2008; Hudnut et al. 2008).

The *ShakeOut Scenario* was used to enhance understanding of the effects of a M_w 7.8 event on critical infrastructure and identify the physical, social, and economic consequences. It provides a realistic illustration of possible fault displacement and shaking throughout the region and useful insight into water supply impacts.

A major SAF earthquake could have severe impacts on aqueduct operations, including the potential to completely disrupt all imported water supplies to Southern California until repairs can be made.

Challenges to Repair and Service Restoration

According to the *ShakeOut Scenario*, the three aqueducts would be significantly damaged by fault movements, ground shaking, liquefaction, and permanent ground movements (differential settlement, lateral spreading, slope and embankment deformations). Afterslip and aftershocks would continue to compromise the aqueducts and slow repair efforts (Davis 2009, 2010; Davis and O'Rourke 2011). Supply and distribution to hundreds of water systems, large and small, would be disrupted, affecting customers and hampering the ability to fight fires.

The duration of disruptions would be a function of damage level and repair time. Restoration times would be affected by resource conflicts (labor, equipment, materials, supplies), transportation difficulties after the earthquake, and additional impairment from aftershocks and afterslip. In addition, fault displacements, shaking, and other ground failures would disrupt other critical lifelines such as highways, railroads, power transmission, oil and natural gas, and fiber optic communication lines, impeding aqueduct repair efforts and severely impacting social and economic activity.

Independent studies based on the *ShakeOut Scenario* noted that repairs to all three aqueducts would likely require more than 6 months. This timeframe is longer than previously anticipated, as described in the following section, revealing new challenges for regional response and recovery efforts (Davis 2009, 2010; Davis and O'Rourke 2011). The study authors recommended "a supply agency coordination team consisting of LADWP, MWD, and the DWR to coordinate aqueduct post-earthquake response and recovery and pre-earthquake mitigation efforts" to improve the regional seismic resilience of the imported water supply systems (Davis and O'Rourke 2011, p. 474).

Economic Impacts

Total losses from the *ShakeOut Scenario* are estimated at $213.3 billion, with approximately 25 percent due to impacts on water systems (regional supply and local distribution): "business interruption from water disruption is greater than 50% of total business interruption losses because of long duration of outage (4–6 months in heavily impacted areas)" (Jones et al. 2008, p. 279). This gross loss in output from water disruption alone is enough to drive the region into a recession. The results assume that the LAA, SWP, and CRA are fully restored to service within 6 months. But as noted above, this assumption may be optimistic. Water disruption longer than 6 months could lead beyond a recession to a regional economic catastrophe (Jones et al. 2008; LADWP 2014).

Countermeasures to the SAF Threat

Historical Measures

The aqueduct systems were generally designed and constructed with knowledge of the SAF hazard and precautions were taken to help mitigate impacts from a fault rupture. For example:

- The City of Los Angeles developed large water supply reservoirs south of the SAF (Lund and Davis 2005).
- The California Aqueduct West Branch crosses the SAF at Quail Lake, a natural body of water that may allow aqueduct water to flow safely across a rupture at that location.
- The SWP is equipped with gate structures at strategic locations along its alignment to allow water to be distributed upstream of the gate while repairs from shaking and fault rupture are made downstream.
- MWD designed the CRA with an additional 2.3 m (7.5 ft) of head to account for potential gradient changes resulting from fault movement. It also used inverted siphons or shallow conduits for crossing identified active traces of the fault to make damaged areas more accessible for repairs, and segmented conduit sections rather than typical monolithic construction to reduce potential damage from displacements (Hinds 1938).
- MWD established emergency storage requirements in 1991, as described below.

Regional Emergency Water Storage

MWD's emergency water storage facilities, located on the coastal side of the fault, can supply the region after a seismic event on the SAF. The emergency storage requirements are based on the potential for a major SAF earthquake to damage the CRA, SWP, and LAA.

Business interruption losses due to water disruption alone could drive the region into a recession or worse.

MWD coordinates with its member agencies to set criteria for emergency storage, assuming that damage from a major SAF earthquake could render the aqueducts out of service for 6 months (MWD 1991). The objective is to ensure water supply and delivery to all member agencies during the outage. This objective allows MWD to provide 75 percent of member agencies' retail demand under normal hydrologic conditions, supplementing local water production to avoid severe water shortages while the aqueducts are out of service.

A major accomplishment to meet local emergency water storage objectives was the completion of Diamond Valley Lake in 2000, which nearly doubled the available emergency supplies in Southern California. In addition, MWD may draw from water-bank agreements during an emergency, if necessary and available.

Ongoing Collaborative Efforts

Resilience by Design

Under Mayor Eric Garcetti, a strategic plan for the City of Los Angeles, *Resilience by Design* (Mayoral Seismic Safety

Task Force 2014; Jones and Aho 2019, this issue), was developed, with specific recommendations for improving the seismic resilience of the Los Angeles water system. One key recommendation is to "create a Seismic Resilience Water Supply Task Force . . . with the LADWP, MWD, and DWR, in an effort to create a collaborative and regional approach to protecting the resilience of our water supply." This recommendation was informed by the *ShakeOut Scenario*, previously mentioned studies of the regional water supply, and LADWP (2014). As part of the Mayoral Seismic Safety Task Force, the LADWP developed an internal water system resilience program (LADWP 2014, which made the same recommendation as Davis and O'Rourke 2011).

Seismic Resilience Water Supply Task Force

In August 2015 a multiagency task force was formed to collaborate on postearthquake response and recovery, undertake studies, and implement mitigation measures to improve the seismic resilience of imported water supplies to Southern California using a regional approach (Clark et al. 2018; Davis et al. 2017). This unprecedented collaboration, which required overcoming institutional constraints and differences in organizational culture to achieve unity of purpose and commitment, has great potential for significantly improving resilience and reducing risk on a regional level.

> *Recovery times would exceed historic planning assumptions and restoration of full aqueduct capacities could exceed 6 months.*

The task force, whose organizational structure consists of a Management Oversight Committee, Seismic Resilience Team, and working groups, is composed of managers and staff from the planning, engineering, and operations groups of each agency: DWR, LADWP, and MWD (figure 3). Recognizing that damage cannot be prevented from a major SAF event, the agencies agreed that "The Task Force will collaboratively develop strategies to mitigate risks and prepare for an event on the SAF with the goal of restoring imported water supplies to Southern California rapidly" (Clark et al. 2018).[2] The task force goals are to

- establish a framework for the agencies to coordinate response and recovery efforts;
- establish a common understanding of individual agency aqueduct seismic vulnerability assessments, projected damage scenarios, and planning assumptions;
- revisit historical assumptions regarding potential aqueduct outages due to seismic events; and
- discuss ideas for improving the seismic resiliency of Southern California's imported water supplies through multiagency cooperation.

The task force will determine steps to develop a coordinated response to emergencies. It already maintains an emergency contact list for agencies to communicate in the event of a major SAF earthquake, and is completing a memorandum of understanding on how they will work together following a serious earthquake. A tabletop exercise was conducted, and a multiagency recovery plan is under development.

Aqueduct Workshop

With an initial focus on aqueduct assessments and mitigation and emergency preparedness and response, the first major task force activity was a workshop to establish a common understanding of seismic vulnerabilities on each aqueduct, revisit historical planning assumptions, and identify action items to increase seismic resilience. The March 2016 workshop focused on (a) potential damage to Southern California's imported water aqueducts from a major seismic event on the southern SAF, (b) potential outage durations for restoration of partial and full aqueduct capacities, (c) identification of regional priorities, and (d) mitigation options (Clark et al. 2017). The format allowed the candid exchange of information and ideas among all participants.

Agency participants considered preparation for and response to the *ShakeOut Scenario* from a regional perspective and were asked, "If all aqueducts were owned and operated by a single agency, what steps should be taken now to mitigate potential damage and what would the priority of repairs be to most rapidly restore imported water deliveries to the region?" From their responses the task force concluded that recovery times would exceed historic planning assumptions, restora-

[2] Other seismic threats will be addressed as warranted.

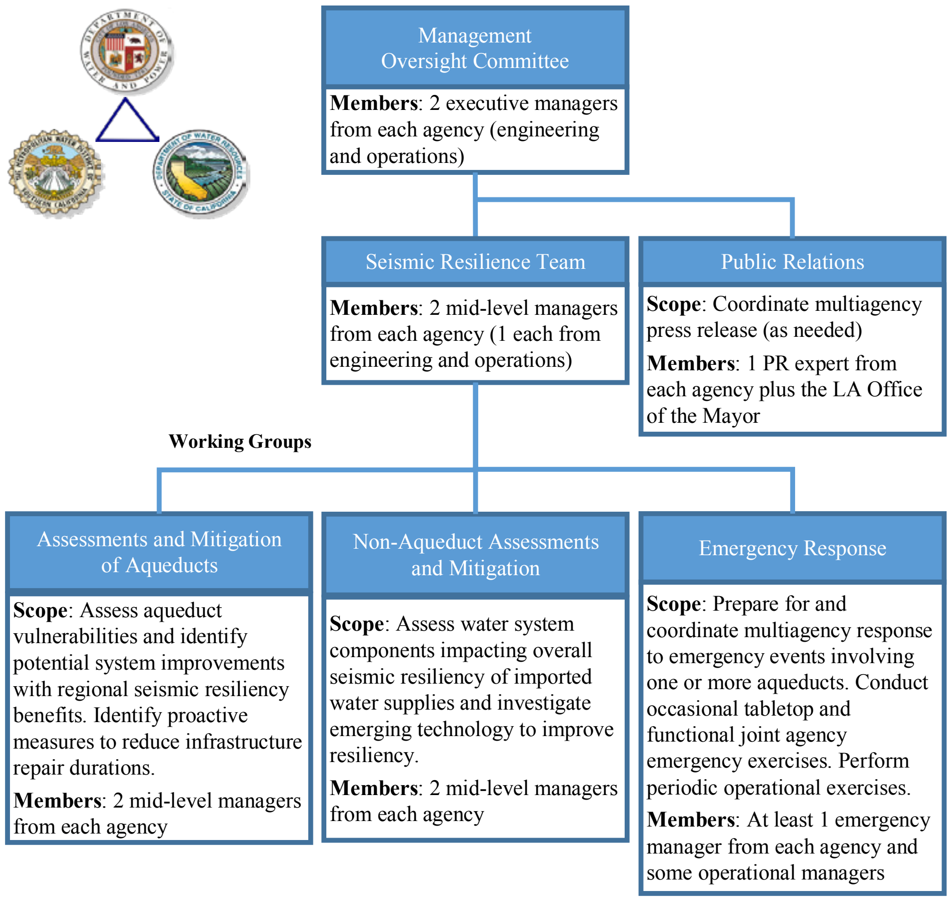

FIGURE 3 Seismic Resilience Water Supply Task Force functions and responsibilities.

tion of partial aqueduct flows could take at least 2 months, and restoration of full aqueduct capacities could exceed 6 months.

Another finding from the workshop is the importance of dependencies of the three aqueduct systems on other lifeline systems for continued operations and the ability to rapidly recover. The most important systems are transportation, communication, and electric power.

The workshop helped develop a consensus on potential outage durations and specific actions to better prepare for large seismic events. The region will be best served if the three agencies

- move forward with recently identified mitigation projects on the CRA and LAA;
- prioritize additional known vulnerabilities on the CRA, LAA, and SWP;
- execute an agreement to allow for a coordinated response to emergency events; and
- develop a joint emergency recovery plan to share resources and prioritize repairs when responding to emergency events.

LADWP's Resilience Expert Panel noted the significance of the nation's largest municipal utility (LADWP), largest water wholesaler (MWD), and largest state-owned water agency (DWR) joining together to address a major hazard for the first time and encouraged the task force to continue working together long into the future. Common issues can be studied more efficiently and Southern California will be better prepared for seismic events if the task force continues its efforts to facilitate coordinated vulnerability assessments, evaluate mitigation options, and develop agreements for coordinated emergency responses to major seismic events.

Soon after the workshop, the agencies developed a 5-year plan to accomplish the identified goals and additional collaborative actions, such as sharing approaches to facility vulnerability investigations and conducting multiagency emergency exercises, including emergency communications. Efforts were also initiated to work with the LADWP power system and Southern California Edison to address aqueduct system dependencies on the electric power systems.

Investigation of Aqueduct Enhancements

The LADWP is developing a seismic enhancement project where the LAA crosses the SAF through the 8 km (5-mile) long Elizabeth Tunnel. It consists of reinforcing the tunnel at vulnerable locations and installing two 61 cm (24-inch) diameter high-density polyethylene pipes for approximately 244 m (800 feet) across the SAF zone (figure 4). The objective is to increase the probability of supplying water across the fault zone for events that do not fully rupture the 2.7 m (9-foot) wide horseshoe-shaped concrete-lined tunnel.

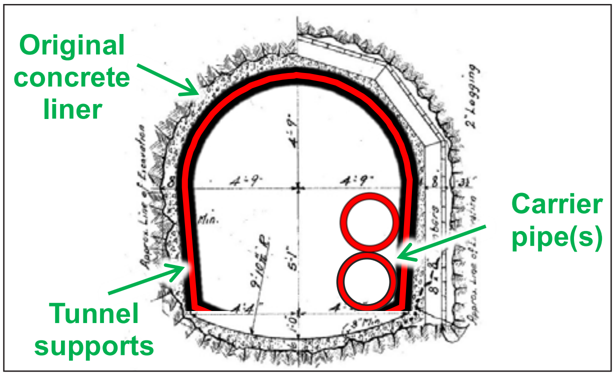

FIGURE 4 Los Angeles Aqueduct seismic enhancement of the Elizabeth Tunnel at the San Andreas Fault crossing. Black = original construction; red = seismic enhancements.

The LADWP is also undertaking other seismic improvements along the LAA and a detailed investigation to characterize the SAF at the Elizabeth Tunnel crossing. These efforts will inform the planning to engineer a solution for the potential maximum fault offset (Lindvall et al. 2018).

MWD is continuing to evaluate and improve the CRA seismic resilience. Recent CRA seismic vulnerability assessments identified the Whitewater Tunnel No. 2 as the most likely component of the system to sustain major damage from a strong earthquake on the southern SAF (MWD 2016; Weldon et al. 2014, 2016). The tunnel's alignment closely parallels the SAF and crosses a splay of the fault. An event like the *ShakeOut Scenario* could damage the tunnel at the fault crossing and shallow sections near the tunnel portals.

Given the specialized nature of tunnel repairs, a workshop convened industry experts in tunnel engineering and construction to identify repair options and estimate repair durations. Participants concluded that, with preevent planning, design, and upgrades, repairs to Whitewater Tunnel No. 2 could be completed within 6 months. These preevent steps include (1) design and construction to strengthen vulnerable tunnel sections near the two portals, (2) design and construction of a new access structure at the west portal, (3) design of a new tunnel section in advance of an earthquake to bypass collapsed and/or blocked portions of the existing tunnel and enable construction to proceed quickly after an event, (4) stockpiling of steel sets needed for construction, and (5) prequalification of tunnel repair contractors. MWD has initiated preliminary design of the tunnel upgrades.

Potential interconnections between the aqueducts are being investigated as one way of increasing system resilience, as discussed during an aqueduct workshop in March 2018. Initial planning efforts are being undertaken to connect the LAA with the California Aqueduct East Branch near the Elizabeth Tunnel north portal. This project increases opportunities both to import water by transferring between the two systems after different types of SAF events and to accelerate seismic improvements along the LAA between the SAF and Los Angeles.

Conclusions

A major earthquake on the San Andreas Fault could disrupt all imported water supplies to Southern California, resulting in serious social and economic impacts to the area's 19 million residents and businesses. Through the Seismic Resilience Water Supply Task Force, the DWR, MWD, and LADWP are working together to minimize these impacts. This unprecedented collaboration will benefit the region in many ways, such as the following:

- comprehensive assessments, evaluations, and studies for the region (for individual aqueducts and how they collectively operate as a regional system);
- clearer understanding of interdependencies both within each system and between the water supply systems and other lifeline systems such as electrical power, transportation, and communication;
- identification of goals and specific recommendations for addressing vulnerabilities; and
- coordination of critical areas for the region's ability to continue operating and recover after an event, including emergency storage needs, resource sharing, and overall emergency response activities.

The result will be a more resilient and sustainable Southern California that will be better protected from major seismic events.

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Trust and Humility in an Ethics of Resilience Engineering

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Rosalyn W. Berne

Risk is an inevitability of the modern condition, deeply woven into technological society and the built environment. An ethical approach to engineering requires looking beyond the technological calculation of risks to ask probing questions about impacts on individuals and society in terms of equity, security, personal safety, and the environment.

The vulnerability of complex technological and constructed systems has been all too vividly demonstrated. In August 2003, for example, the great Northeast blackout, triggered when a sagging power line touched some tree limbs in northeastern Ohio, was rapidly "complicated by human error, software issues, and equipment failures, [leading] to the most widespread blackout in North American history. More than 50 million people across eight northeastern US states and parts of Canada were left without power for at least 24 hours, and many of them were in the dark for weeks" (Taylor 2018).

> The loss of electricity . . . shut down airports, subways, trains, and tunnels. . . [and] suspended the operation of automatic doors, elevators, and entire drinking water utilities. It forced hospitals to run on limited power produced by back-up generators. Cell phone towers, cash registers, and ATMs went out of commis-

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This column is produced in collaboration with the NAE's Center for Engineering Ethics and Society to bring attention to and prompt thinking about ethical and social dimensions of engineering practice.

> sion. In New York City, evening commuters stranded in a blackened city were forced to walk home because the city's public transportation system had ground to a halt.[1]

More recently, the record flooding in the Midwest that began in March 2019 affected 75 cities, 65 counties, and 4 tribal areas in Iowa, Nebraska, South Dakota, and Wisconsin. In Iowa at least 30 levee failures flooded towns and highways. The US Army Corps of Engineers reported that "the majority of the levee system along the Missouri River…is compromised. The bulk of the levees remain overtopped or breached" (USACE 2019). The economic impact was projected to "reach $2 billion as farmers struggle with damaged grain, massive cleanup, and impassable roads and bridges to fields and livestock" (Eller 2019).

These two large-scale disasters compromised critical infrastructure and put millions at risk of injury, disease, or death. Too often, vulnerable communities are the hardest hit (Krause and Reeves 2017), as seen in two other disasters. Hurricane Katrina in 2005 displaced thousands of residents in the Lower Ninth Ward, where the average household income was two-thirds that of New Orleans overall. And the contamination of drinking water in Flint, Michigan—at least partially caused by lack of attention to the resilience of Detroit's water distribution system—also disproportionately affected poorer citizens.

What are the ethical obligations of engineers to design resilient systems with the capacity to protect *all* who are at risk from natural disasters? There is a case to be made that social inequality should be considered in engineering design and development (Jasanoff 2007). In particular, a perspective and approach imbued with humility acknowledges both the possibility of unforeseen consequences and the need for plural viewpoints and collective learning (Jasanoff 2003, p. 240). Why humility, rather than the conventional virtues of ethical engineering practice of impartiality, honesty, equity, and fairness, described in the National Society of Professional Engineers code of ethics?[2] Because

> [h]umility instructs us to think harder about how to reframe problems so that their ethical dimensions are brought to light, which new facts to seek and when to resist asking science for clarification. Humility directs us to alleviate known causes of people's vulnerability to harm, to pay attention to the distribution of risks and benefits, and to reflect on the social factors that promote or discourage learning. (Jasanoff 2007)

Another approach is sociotechnical design, which incorporates ethics considerations by giving equal weight to social and technical issues when new systems are being designed and according the rights and needs of humans as much priority as the nonhuman parts of a system (Mumford 2000).

It is true that foresight of risk is not always possible. Disasters have been characterized as morality tales about unforeseen consequences as well as carelessness and overreaching, mistakes in dealings with technology (Jasanoff 2016, p. 60): "Such lessons are particularly important in an age when, partially as a result of increasing wealth and population density and partly because of the mobility of capital and industry, the likely impact of disasters has risen while their causes have become less easy to anticipate and pin down."

The essence of engineering is to serve people and society (NAE 2017, p. iv), making it inherently an ethical undertaking, and the profession's ethical practices are largely responsible for the considerable public trust the field generally enjoys. For the engineering profession to uphold the public's trust and the expectations of engineered systems to keep people safe from harm, resilience engineering must be guided by ethics.

[1] Blackout: A case study of the 2003 North American power outage. George Mason University Center for Infrastructure Protection and Homeland Security. Retrieved from https://cip.gmu.edu/wp-content/uploads/2015/08/Blackout-Learner-Version.pdf.

[2] https://www.nspe.org/resources/ethics/code-ethics

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An Interview with . . .

Ekua Bentil, World Bank Education Specialist

RON LATANISION (RML): Thank you for joining us today. We're delighted to have this opportunity to speak with you, and happy to have an electrical engineer who is involved with the World Bank and finance and all kinds of things. How did you choose to study electrical engineering?

EKUA BENTIL: I grew up from the ages of 6 to 10 in Liberia. When the Civil War broke out there we suddenly had to leave everything and flee for our lives and we returned to Ghana, where my family is from.

I was in the 5th grade at the time and realized that I really loved math. In high school, I excelled in and loved math and physics, especially the practical aspects of physics. When I was about to go to college I did a bit of research to see what would be a good area for me to study. I did a lot of reading and I talked to my dad, who's a physics professor, and he said "see what you like" and I just picked electrical engineering.

CAMERON FLETCHER (CHF): How did you end up at Bryn Mawr? That happens to be my alma mater as well.

DR. BENTIL: Wow, small world. I had done a year of electrical engineering in Ghana and then applied to schools in the US. My high school, Wesley Girls' High School, is an all-girls boarding school (boarding high schools are common in Ghana). When I was looking at schools in the US I came across Bryn Mawr, a women's college, and I saw that they had a very strong physics program. They had a 3-2 engineering program that I could eventually participate in to get back into electrical engineering. So although I was in an electrical engineering program in Ghana, when I saw Bryn Mawr's physics program I got very interested. Once I enrolled, I was not disappointed. The program was very strong, I liked the fact that the school was small, and they gave very generous scholarships so I got almost a full ride to do physics at Bryn Mawr.

RML: I see in your CV that the 3-2 dual bachelor's degree involves Caltech. What is that program?

CHF: And how did you manage it across the country?

DR. BENTIL: When I initially applied to Bryn Mawr they had this 3-2 engineering program only with the University of Pennsylvania. When I got to my second year, I learned that they had the 3-2 engineering program with Caltech as well. To prepare myself, I took some engineering classes at Swarthmore College, in addition to my physics classes, and applied to Caltech and got in at the end of my third year at Bryn Mawr. So you do 3 years at a liberal arts college and then go to a university where you do 2 years of basically a full engineering undergraduate degree. It's like you're transferring but you have to meet the minimum requirements to earn degrees at both institutions. I graduated with two undergraduate degrees: in physics from Bryn Mawr and in electrical engineering (EE) from Caltech.

There were phenomenal students at Caltech—people who just wanted to do science. That was the environment there. Because I had to meet the minimum requirements of the EE program in two years, it felt like

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This conversation took place April 22, 2019. It has been edited for length and clarity.

I was drinking from a fire hose, but I really wanted to do this. At any point in time, I was in first-, second-, and third-year EE classes in the same term.

I spent a lot of long hours in the labs. I would go in at night and come out and it's daylight. It felt like I was emerging from the dungeons! But I was determined to push through because I loved engineering and was passionate about it, so I knew I had to do whatever I had to do.

RML: And your thesis research at Princeton focused on semiconductor devices. What was the specific nature of your thesis work?

DR. BENTIL: My research group at Princeton did a lot of work in the mid-infrared range, dealing with semiconductors and how to fabricate lasers, detectors, and other devices that could be incorporated into gas sensors. Mid-infrared lasers are ideal for sensing gases because a lot of gases have unique fingerprints in the mid-infrared range. In my group, the core work was developing and optimizing what's known as quantum cascade lasers, which work very well in sensors used in detecting gases in the mid-infrared range.

I ended up doing a little of everything. I did some device-level work and then system-level work as well. I integrated the quantum cascade laser, mirrors, detectors, and other components in a system and built a gas sensor.

I also worked with students at the University of Cape Coast in Ghana to deploy the laser sensor in a fishing community, where they processed a lot of smoked fish over firewood—smoked salmon and other types of fish, very common in Ghanaians' diet. Women would do this type of work and spend long hours in the smoke, and there were a lot of anecdotes about women getting respiratory problems and other related health issues.

I wanted to see if we could make a sensor that we could deploy and use to identify the gases the women were inhaling from the wood smoke. I also wanted to work with students in Ghana and to bring over some of the technology and the work we were doing, to in some sense give back to Ghana.

RML: That led into your current activities at the World Bank, didn't it?

DR. BENTIL: Yes. I had always wanted to have a big research complex in Ghana where we would do research into the latest—well, I wasn't sure exactly what, something about semiconductors and maybe sensors, building off the work I did at Princeton. I always had that desire to give back, since I had done a year of university in Ghana before coming to the US and also grew up on a university campus. So I hoped I could go back and add value to the training of future engineers and scientists and to the applied science research culture.

I wanted to find a way of helping to develop the research culture in African universities, specifically in Ghana. I dreamed of having a big complex where researchers would come and do research, with different facilities, labs, accommodation, child care, libraries—I had the image in my head.

I always wanted to find a way of helping to develop the research culture in African universities.

But when I was graduating from Princeton, I had applied for research positions at different companies and had an offer from Intel, but Goldman Sachs had also reached out. They had picked up my resume and wanted to interview me. I hadn't applied to Goldman Sachs and never would have thought of applying there, but I decided to give it a try since they had found my resume and reached out. So I went in and did the interview and 12 interviews later, they offered me the job.

While I worked at Goldman Sachs, always in the back of my mind I was aware that deep down the core of my heart was to build capacity in Africa . I knew I would really love to do it. More and more my heart ran closer to that.

I had been at Goldman Sachs about 3½ years when I got an opportunity to go to an event where I met a World Bank manager and she invited me to come talk to her. When I got there as we talked she mentioned "this initiative that we just started, the Partnership for Skills in Applied Sciences, Engineering, and Technology (PASET), to build capacity in Africa."

RML: It sounds like your dream.

DR. BENTIL: Exactly. It was interesting because I had started asking people who worked in the development world what it would mean for someone with my background to do that type of work. When I was looking at changing jobs from Goldman, I wondered, 'Do I go back into academia or do I look into the development world? What are my options?'

It was a risky jump for me to leave Goldman at the time because the position she was offering was a consultancy and my husband had just started his law PhD at Georgetown and we have two kids. So it was a risk but we talked about it and he said, "This is what you've always wanted to do. Go try it out and see where it leads." I did the consultancy for one year at the World Bank, and then I got hired full time.

RML: At Goldman Sachs you were working as a risk modeler, which must have involved largely computational skills, is that correct?

DR. BENTIL: Yes, programming, computational skills, and some finance, which I had to learn on the job—I came in with zero knowledge of finance. In fact, when they were interviewing me several interviewers basically said, "What are you doing here?" And I consistently said, "I'm here because your manager picked up my resume and invited me to come and interview with you."

RML: The word risk piqued my interest because risk management is, especially in engineering, very important.

For obvious reasons, development partners are more interested in health and agriculture, so engineering schools in Africa are struggling.

I'm curious about applied research in the program you're leading with the World Bank. What kinds of research and projects are being done in the countries in West and Central Africa?

DR. BENTIL: With the new Africa Centers of Excellence (ACE) project (the third in the series of ACE projects) that I'm leading now we have 49 centers and 7 colleges of engineering that I work with across 12 countries in West and Central Africa.[1] It's a big opportunity. When you look at the work these centers are doing, we have broad categories of the STEM fields as well as health and agriculture. We have centers looking into the genomics of infectious diseases, the Internet of Things, cybersecurity, water, power, coastal resilience, climate change, environmental risk, mining and the environment—the whole gamut. It's a lot of different areas and sectors where Africa needs capacity both in training people and in doing applied research.

RML: In the countries with the program, are there engineering students actively involved in research on, for example, water or energy or agriculture? Is it funded through the World Bank and the governments of the countries that are involved? How does all this work?

DR. BENTIL: There are two sets of programs that I work on: PASET, which brought me into the World Bank and is across all of Africa, and the ACE project. Under the ACE project, the governments get loans from the World Bank; for some governments it's a mix of loans and grants, but for the most part these are loans to the governments, and from these the governments give grants to the centers, which are selected competitively.

And then we use a results-based funding mechanism that incentivizes the centers toward excellence. Core results are predetermined and each result is allocated a dollar amount if achieved. As centers achieve the results, they receive funding for their planned activities; on average, centers get about $5 million for 5 years (the exact amount varies from country to country).

The centers are expected to develop their academic programs and seek international accreditation of them. They need to train a certain number of students at the master's and PhD level (the engineering schools that we look at have undergraduates as well). They need to have research published in international peer-reviewed journals; and their research is evaluated for its relevance and impact on development.

We also promote strong linkages to industry—local, regional, and multinationals. We encourage the centers to form regional networks based on their thematic focus areas and to also partner with universities in the US, Europe, Korea, China, Japan, India, Canada—across the world.

I think in the past in Africa, a lot of focus was on fixing basic education before making efforts in higher education. The ACE project for the World Bank was the first regional project in higher education in Africa. It has really changed the narrative, which is good,

[1] The 12 countries are Benin, Burkina Faso, Cameroon, Côte d'Ivoire, Djibouti, the Gambia, Ghana, Guinea, Niger, Nigeria, Senegal, and Togo.

and now we're on the third ACE project, which I'm leading.

Also importantly, a lot of funding in Africa focuses on agriculture and health. Engineering programs are hardly ever supported. For obvious reasons, development partners have been more interested in health and agriculture, so engineering schools in Africa are struggling.

It's good that now the focus is shifting, especially as we move toward conversations around the digital economy and how to get Africa there, which will be through a lot of these computer science and engineering programs that we have begun actively supporting.

CHF: Tell us about your work, specifically the kinds of things you do.

DR. BENTIL: Under the ACE project, my work is to engage with the governments, contribute to the design of the project, and manage its implementation, including compliance on environment and social safeguards, procurement, and financial management.

As we move toward implementation, we do monitoring and evaluation of how the centers are performing with respect to both various results targets they set and the overall objectives of the project. I make sure that we are progressing in line with those targets. It is a lot of constant problem solving. We also have supervision missions where we work with experts in the various thematic areas. They go and assess the centers along with some of my colleagues on the ground to see how they are performing; if there are any problems, we work through them with the centers.

RML: These are experts from the university system in Africa? Or are they external to Africa? Where are they from?

DR. BENTIL: We bring in experts from all over. We gather resumes and recommendations and then we bring these experts in to work with us because we can't do it all and we are not experts in all of these thematic areas.

On the PASET program, we have funding for original academic scholarship and innovation from some African governments and from Korea to really push scholarships for PhD training in applied sciences, engineering, and technology fields. I worked on that program in the early stages of designing and am still one of the coleads.

The second thing I do with PASET is I lead a benchmarking initiative. We get data from African universities and assess their performance with respect to some benchmarks. It involves general data collection and how to use the data for strategic planning, which is a struggle for most African universities. We are working with them to understand the importance of management information systems and how to set them up. Because if you don't have data how do you plan? You have to do planning for your university.

Ekua Bentil speaking at a PASET University Benchmarking Capacity-Building Workshop in Abuja, Nigeria, June 2016.

RML: Do you have any collaboration with engineering schools in the US or Europe?

DR. BENTIL: For ACE the way we're currently working is that the individual centers, because there are so many, form and manage their own collaborations. A number of them have collaborations with institutions in the US.

On the PASET side, we are working with US universities to determine those that would be interested in hosting some of the students in the scholarship program. Worcester Polytechnic Institute has shown interest, as have some faculty from MIT and Rutgers, among others. We also have collaborations with the Korea Institute of Science and Technology and with Seoul National University, and we are developing several other partnerships.

As I stated earlier, with the ACE project we are now supporting engineering schools. There's a lot of peer-to-peer learning. We are very interested in doing and knowing more. What are some of the top universities in the US doing in their engineering education that the African universities could learn from and vice versa?

CHF: Ekua, I'm wondering how your engineering mindset informs your approach to your work.

DR. BENTIL: Well, I tend to be too focused on details. Sometimes it's good but sometimes I need to step back and look at the big picture. I think because of my engineering training there's a level of attention to detail, accuracy, that I bring to the table. But sometimes my colleagues encourage me to "just let it go, it'll be okay!"

And there's a level of persistence as an engineer. Especially let's say if you're an engineer who works on a plane design, you need to make sure you are precise because even a small error could cause serious problems. There is some element of that in my work—I want to make sure things are right before I move on. I think I add some value in that way.

As an engineer, you need to make sure you are precise because even a small error could cause serious problems.

And there's also the systematic approach to learning that I use when I take on a new project. I compartmentalize it into buckets in terms of how I should work through it and the flow of steps involved. I try to have a picture of that in my head and then I can put it on paper.

CHF: That sounds very useful given the complexity and scope of the projects you're working on and leading.

RML: Those are very healthy engineering instincts. They play a very important role in trying to roll out and extend and cultivate a program that has such important consequences in terms of the people who are involved.

Along those lines, what does the World Bank view as success? When the World Bank looks at this project in 5 years, what will they be looking for?

DR. BENTIL: For the technical part of it, the World Bank will consider how much of the funding was disbursed, because the disbursements of a results-based project are linked to how well the centers are performing in terms of reaching their results: as they meet results, they get the funding. So that's the first thing the World Bank looks at: disbursement.

We are already moving the needle on quality. With the first series of the ACE project (as I said we are in phase three), a number of centers got international accreditation for the first time for their academic programs, which is a very big deal and we will continue to encourage this. A number of countries participating in the project ask, "How can we replicate this at our other universities?" They are seeing that these centers in the ACE projects are making a big difference.

The World Bank will also look at the impact on the direct beneficiaries of the project, including the students, faculty, and their institutions. One of the things we're looking for in this third phase is institutional impact. We wouldn't want to have centers being like an oasis, isolated, where the centers are healthy but their universities are not. How do we link the centers more strongly to their institutions in improving financial management, procurement processes, data management, management/governance of processes in the university, development of regional strategies?

In my view, success is being able to influence change and seeing graduates of these programs excelling globally in the world of work and the research outputs from the programs transforming the continent.

CHF: Is there a plan for these programs to become self-sustaining? I can't imagine that the World Bank plans to support them indefinitely.

DR. BENTIL: That's a very good question. Sustainability is a big question that we deal with. Five years is a really short time to expect a center to be able to stand on its feet. Usually it would take 10 to 15 years for a well-performing center that has good revenue to build its relationships and its own stream of funding outside of the development partners. Eighteen of the centers from the phase one ACE project are being supported in the this third phase for another five years.

CHF: They are being supported by other sources or they have their own sources of funding?

DR. BENTIL: They are being supported by the World Bank in this third phase. Most of them had $8 million in the first phase, and in the third phase they have a little less than that; the idea is to give them some padding. One of the results that we incentivize them with is to be able to generate external revenue, so we are urging them to form strong linkages with industry so that industry takes an interest in what they are doing and will support them. We also encourage their govern-

Ekua Bentil speaking at an ACE project regional workshop in Djibouti, February 2019.

ments to invest in grant programs that these centers can also apply for. Such grant programs are not common in a lot of African countries.

How can they provide consultancy work for industry? How can they develop and offer short courses for professionals in the ministries in their countries to bring in revenue? Some of the centers are doing that and have been successful in bringing in revenue. We hope we can get a good number of centers able to stand on their feet at the end of this phase.

CHF: You mention linkages with industry. Is this domestic and international corporations?

DR. BENTIL: It's a mix. For example, at the regional project level, we have been trying to engage with companies that fall under what we call digital development—Intel, Google, LinkedIn, Facebook, Ericsson. A number of these are multinationals, with offices in Africa. We encourage the centers to work with these companies directly. It helps that the World Bank has convening power and we try to leverage that to invite and bring these companies to the table to work with the centers.

The centers also have to look around their own countries. For example, the power/energy centers should look at the utilities companies for partnering, whether they are national or regional.

CHF: Is there discussion of expanding this program from Africa to other areas of the world, such as Asia or South America? Or has this already been done?

DR. BENTIL: There was a similar project in India that the World Bank had led and which the ACE projects built on. With the third phase we have Djibouti, which is part of the World Bank MENA classification (Middle East and North Africa).

I don't know what could be next, whether we're going to have other centers in the MENA region or elsewhere in the developing world. But there's a lot of peer-to-peer learning and sharing of our knowledge that happens internally and so elements of the ACE projects are being incorporated into other regional and national-level education projects within the World Bank.

CHF: Yes, it sounds like a very useful model.

RML: It is a great model. And I think it's especially important, from the point of view of everyone involved—the World Bank, the African nations, national governments, and the students—to have these important performance metrics that you've described. When you can say that your center is being accredited and your students are being recognized for their achievement and the individual programs are developing resources, all of that's really critical to making a sustained and significant effort. And I can see you're a major player in that.

We need to give people opportunities and invest in human capital. This is critical in places where people feel that there is no hope.

The only question I have left is, how old are your kids?

DR. BENTIL: I have a 9-year-old and a 6-year-old.

RML: And doesn't your work require a fair amount of travel on your part?

DR. BENTIL: Yes, I travel every other month. I try to give myself at least one month off because of my family but every other month I'm on a plane going somewhere.

RML: Oh my goodness. How do you manage being away so much? That would take some considerable effort.

DR. BENTIL: I think that's one of the most difficult parts of my work. I usually cook up a storm and store it in the freezer right before I leave, so it's a little intense in the house around that time. All my husband will have to do is microwave the food and get the kids moving to school and wherever else.

RML: That's a good compromise between mother and father and kids.

DR. BENTIL: My husband has definitely been really incredible in his support to get me where I am now. He would always hear me talk about what my passion was and he would tell me to write it down, particularly when I first felt strongly about setting up this big research complex in Africa. I've even gone to speak to my advisor from Princeton about it—I'm still in touch with her.

RML: Who was your Princeton advisor?

DR. BENTIL: Claire Gmachl, an incredible personality. She's Austrian.

CHF: Ekua, we are mindful that we're drawing to the end of our hour and I'm sure you have many other demands on your time, but we do want to ask, Is there any message you might like to convey to our readers?

DR. BENTIL: Yes. I think it's important to recognize that when one part of the world suffers or is not well developed, the developed parts end up suffering as well. We see a lot of migration and the issues related to that. And we're dealing with a lot of global problems.

When people of a community learn that they are able to solve their own problems, I think that's the best gift we can give to any community. So investment in human capital is core, and we should bear in mind that, when given the opportunities, people can really make an impact in their own communities, and this will eventually support the work that's being done globally and ease some of the global challenges we've been dealing with in the world.

We need to give this opportunity to all people and getting that message across is critical, even, or especially, in places where people feel that there is no hope. Building the human capital potential in those places is key in making a difference in our world.

CHF: That's a terrific message.

RML: Yes, it is. I think you're a living example and a testimonial to that philosophy. I applaud what you're doing. Thank you so much, Ekua.

CHF: Yes, what a pleasure. Thank you, Ekua.

DR. BENTIL: Thank you too.

NAE News and Notes

NAE Newsmakers

Gilda A. Barabino, Daniel and Frances Berg Professor and dean, Grove School of Engineering, City College of the City University of New York, has been included in the **inaugural list of Notable Women in Tech** in *Crain's New York Business*. The list is part of a series to recognize and celebrate women in the workplace across industries. Selection is based on professional achievement, civic and philanthropic work, and involvement in organizations (inside or outside their firm) where they mentor other women and/or promote diversity.

Emily A. Carter, dean, School of Engineering and Applied Science, Princeton University, received the **2019 Distinguished Alumni Award** from the California Institute of Technology. Dr. Carter was recognized "for her visionary leadership in sustainable energy and engagement with the broader scientific community and for her development of powerful theoretical methods based on quantum mechanics that have greatly influenced chemistry and engineering."

Akhil Datta-Gupta, Regents Professor and L.F. Peterson '36 Chair, Harold Vance Department of Petroleum Engineering, Texas A&M University, received the **2019 SURA Distinguished Scientist Award** on March 28 in Atlanta. The annual honor goes to a research scientist whose extraordinary work fulfills the Southeastern Universities Research Association (SURA) mission to advance collaborative research and education and to strengthen the scientific capabilities of its members and the nation. Dr. Datta-Gupta's pioneering work on high-resolution modeling of fluid flow in petroleum reserves is known throughout the world.

Jack J. Dongarra, University Distinguished Professor, University of Tennessee, Knoxville, and **H. Kumar Wickramasinghe**, UCI Distinguished Professor and Nicolaos G. & Sue Curtis Alexopoulos Presidential Chair in Electrical Engineering and Computer Science, University of California, Irvine, have been elected **fellows** by the **Royal Society of London**.

Amit Goyal, director, RENEW Institute, SUNY Empire Innovation Professor, University of Buffalo (UB), was awarded the **UB President's Medal** in recognition of extraordinary service to the university. The honor was presented during commencement ceremonies in May.

Thomas E. Graedel, Clifton R. Musser Professor of Industrial Ecology Emeritus, Yale University, received Washington State University's **2019 Regents' Distinguished Alumnus Award**. Dr. Graedel was honored for his contributions to the understanding of atmospheric chemistry and his work to develop the field of industrial ecology. He received the award April 2 at a presentation on the Pullman Campus.

Laura M. Haas, dean, College of Information and Computer Sciences, University of Massachusetts Amherst, has been chosen to receive the IEEE Computer Society's **2019 Computer Pioneer Award**. She is cited "for pioneering innovations in the architecture of federated databases and in the integration of data from multiple, heterogeneous sources."

The Association for Computing Machinery has named **Geoffrey E. Hinton**, Distinguished Researcher, Google Inc.; **Yann A. LeCun**, director, Facebook AI Research; and Yoshua Bengio the recipients of the **2018 ACM A.M. Turing Award**. They received the award for conceptual and engineering breakthroughs that have made deep neural networks a critical component of computing. Working independently and together, they developed conceptual foundations for the field, identified surprising phenomena through experiments, and contributed engineering advances that demonstrated the practical advantages of deep neural networks.

Allan S. Hoffman, emeritus professor of Bioengineering, University of Washington, was **honored by the Society for Biomaterials** with a "thought leader symposium" at the 2019 SFB annual meeting in Seattle April 3–6. Dr. Hoffman was recognized for his seminal leadership in the field of biomaterials and his many contributions to the biomaterials community over several decades. The symposium focused on his pioneering efforts in the development of smart polymeric materials and new drug delivery systems.

Frederick J. Leonberger, principal, EOvation Advisors LLC, has been named the winner of the **2019 David Richardson Medal**

by the Optical Society. The award recognizes those who have made significant contributions to optical engineering, primarily in the commercial and industrial sector. Dr. Leonberger's citation reads "For innovative development, technical leadership, and commercialization of guided wave photonic components, especially integrated optical modulators, that have had major applications in fiber optic communications, CATV, and sensing."

Asad M. Madni, independent consultant, and retired president, chief operating officer, and CTO, BEI Technologies Inc., has been honored by IEEE-Eta Kappa Nu (HKN) with the creation of the **IEEE-HKN Asad M. Madni Outstanding Technical Achievement and Excellence Award**. The award was established to recognize and honor Dr. Madni's nearly 50 years of technical and philanthropic accomplishments and visionary leadership. It will be presented annually beginning in 2020 to a practitioner in the IEEE technical fields of interest whose invention, development, or innovation has had worldwide impact.

Chad A. Mirkin, director, International Institute for Nanotechnology, and George B. Rathmann Professor of Chemistry, Northwestern University, will receive the **2019 Perkin Medal** from the Society of Chemical Industry, America Group. The medal, considered by many to be the highest honor in American industrial chemistry, is given in recognition of his contributions to nanotechnology and nanochemistry, and the many diagnostic, therapeutic, and materials applications that have derived from his discoveries. It will be presented to Dr. Mirkin in September.

C. D. Mote, Jr., NAE president, has received the **2019 USC Viterbi Lifetime Achievement Award**. It was presented April 11 in Los Angeles.

Cherry A. Murray, professor, School of Engineering and Applied Sciences, Harvard University, has been **elected cochair of the Inter-Academy Partnership (IAP) for Science**. She was chosen during the triennial IAP General Assembly in Songdo, South Korea. The IAP is guided by a steering committee of the six cochairs of its three constituent networks—health, research, and science.

Bradford W. Parkinson, Edward C. Wells Professor of Aeronautics and Astronautics Emeritus, Stanford University, and **James J. Spilker Jr.**, executive chair, AOSense Inc., and consulting professor in Stanford's Aeronautics and Astronautics Department, have received the **2019 Queen Elizabeth Prize for Engineering**. They were chosen for their pioneering work in the development of the Global Positioning System (GPS).

Nicholas A. Peppas, Cockrell Family Regents Chair in Engineering #6, professor, and director of the Institute for Biomaterials, Drug Delivery, and Regenerative Medicine, University of Texas at Austin, received the **Adam Yarmolinsky Medal** from the National Academy of Medicine during its annual meeting in October 2018. He received the award "for distinguished service outside of the health and medical sciences and for contributing to the mission of the National Academy of Medicine." Dr. Peppas is the first engineer to receive the medal.

Roderic I. Pettigrew, CEO, EnHealth, Health Science Center and College of Engineering, Texas A&M University, has received the **SEC Faculty Achievement Award**. The award is given to one faculty member from each school in the Southeastern Conference to recognize professors with outstanding records in research and scholarship. Dr. Pettigrew was selected to highlight his innovative thinking and transformative plans for EnMed, helping to create a new generation of professional, the "physicianeer."

Yahya Rahmat-Samii, Northrop Grumman Professor, Electrical and Computer Engineering Department, University of California, Los Angeles, received an **Ellis Island Medal of Honor** on May 11 at a ceremony on Ellis Island. The medals are awarded to distinguished US citizens who exemplify a life dedicated to community service.

Virginia M. Rometty, chair, president, and chief executive officer, IBM Corporation, has been honored with the **2019 Edison Achievement Award**. She is recognized for creating an environment where innovative solutions are being developed to advance business and make the world a safer and more productive place.

Alton D. Romig Jr., NAE executive officer, received the **Distinguished Career in Engineering Award** from the Washington Academy of Sciences during its Annual Awards Banquet on May 9.

The **inaugural Charles P. Thacker Breakthrough in Computing Award** has been conferred on **Mendel Rosenblum**, professor, Computer Science Department, Stanford University. The award was established by the Association for Computing Machinery to recognize individuals or groups who have made surprising, disruptive, or leapfrog contributions to computing ideas or technologies. Dr. Rosenblum is recognized for reinventing the virtual machine for the modern era and thereby revolutionizing datacenters and enabling modern cloud computing. The award was presented June 15 at ACM's annual banquet in San Francisco.

Molly Shoichet, University Professor, University of Toronto, has been named a **2019 Distinguished Woman in Chemistry or Chemical Engineering** by the International Union of Pure and Applied Chemistry.

Ivan E. Sutherland, visiting scientist, Department of Electrical and Computer Engineering, Maseeh College of Engineering and Computer Science, Portland State University, has been awarded the **BBVA Foundation Frontiers of Knowledge Award** for revolutionizing human-machine interaction through computer graphics and virtual reality.

Warren M. Washington, senior scientist, Climate and Global Dynamics Division, National Center for Atmospheric Research, has been **honored by the Pennsylvania State University**. When he graduated from Penn State in 1964, Dr. Washington made history by becoming the second African-American to earn a doctorate in meteorology nationwide. During a dedication ceremony on May 17, Penn State changed the name of Building 328 at Innovation Park to the **Warren M. Washington Building**, the first to be named for a university innovator and pioneer. The building houses the National Weather Service.

Jennifer L. West, Fitzpatrick Family University Professor of Engineering, Duke University, has won the **Dean's Award for Excellence in Mentoring**.

Richard N. Wright, retired director, Building and Fire Research Laboratory, National Institute of Standards and Technology, has been presented the **Albert Nelson Marquis Lifetime Achievement Award** by Marquis Who's Who.

Eli Yablonovitch, professor of electrical engineering and computer sciences, University of California, Berkeley, has been selected by the Optical Society to receive the **2019 Frederic Ives Medal/Jarus W. Quinn Prize**. A distinguished leader in optics and photonics research, Dr. Yablonovitch is being honored "for diverse and deep contributions to optical science including photonic crystals, strained semiconductor lasers, and new record-breaking solar cell physics."

The American Institute of Aeronautics and Astronautics has announced the 2019 winners of its prestigious awards. **John L. Junkins**, Distinguished Professor of Aerospace Engineering, Royce E. Wisenbaker '39 Chair in Engineering, and director, Hagler Institute for Advanced Study, Texas A&M University, is the **AIAA Goddard Astronautics Award** winner. He was chosen "for advances in aerospace research and education, for creating an institute for promoting scientific excellence, and for enabling contributions in spacecraft navigation, dynamics, and control." **Philippe R. Spalart**, senior technical fellow, Flight Sciences, Boeing Commercial Airplanes, won the **AIAA Reed Aeronautics Award** for "contributions in the simulation of complex turbulent flows enabling the prediction and optimization of aerodynamic characteristics of aerospace vehicles."

At its annual meeting in April, the National Academy of Sciences elected the following NAE members and foreign members: **Joanna Aizenberg**, Amy Smith Berylson Professor of Materials Science and professor of chemistry and chemical biology, SEAS, Harvard University; **Paula T. Hammond**, David H. Koch Professor of Engineering and head, Department of Chemical Engineering, Massachusetts Institute of Technology (she is now a member of all three Academies); **David Harel**, The William Sussman Professor of Mathematics, Department of Computer Science and Applied Mathematics, Weizmann Institute of Science; **Jennifer A. Lewis**, Hansjörg Wyss Professor of Biologically Inspired Engineering, John A. Paulson School of Engineering and Applied Sciences, Harvard University (elected to the NAS in 2018 but not present for the induction ceremony that year); **Krzysztof Matyjaszewski**, J.C. Warner University Professor of Natural Science, Carnegie Mellon University; **Jens Nielsen**, professor, Department of Biology and Biological Engineering, Chalmers Institute of Technology; **Scott J. Shenker**, professor, Department of Electrical Engineering and Computer Science, University of California, Berkeley; **Zhigang Suo**, Allen E. and Marilyn M. Puckett Professor of Mechanics and Materials, School of Engineering and Applied Sciences, Harvard University; and **Matthew V. Tirrell**, Pritzker Director, Institute for Molecular Engineering, University of Chicago.

NAE President, Foreign Secretary, and Councillors Elected

This spring the NAE elected its president and foreign secretary, reelected two incumbent councillors, and elected two new councillors. All terms begin July 1, 2019.

Elected to a six-year term as NAE president was **John L. Anderson**, President Emeritus and Distinguished Professor of Chemical Engineering at Illinois Institute of Technology. Elected to a four-year term as NAE foreign secretary was **James M. Tien**, Distinguished Professor and Dean Emeritus at University of Miami.

Josephine Cheng, entrepreneur and retired vice president of International Business Machines Corporation, and **Alan I. Taub**, professor of materials science and engineering at University of Michigan and retired vice president of global research and development at General Motors Company, were reelected to three-year terms as councillors. Newly elected to three-year terms as councillors were **James O. Ellis Jr.**, US Navy (retired) and Annenberg Distinguished Visiting Fellow at the Hoover Institution, Stanford University, and **Robin K. McGuire**, senior principal at Lettis Consul-

John L. Anderson

James M. Tien

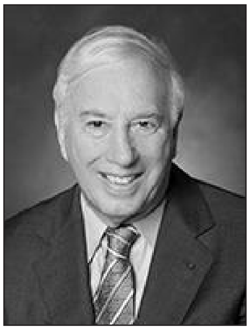
Josephine Cheng

Alan I. Taub

James O. Ellis, Jr.

Robin K. McGuire

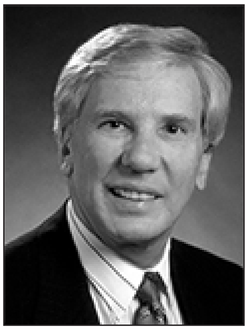
Howard B. Rosen



C. D. Mote, Jr.

Ruth A. David

David E. Daniel



C. Paul Robinson

tants International Inc. (LCI). **Howard B. Rosen**, independent consultant, lecturer at Stanford University, and former president, ALZA Corporation, a Johnson & Johnson Company, was elected by the NAE Council for a two-year term to fill the seat vacated by John Anderson.

On June 30, 2019, **C. D. Mote, Jr.**, completed a six-year term as NAE president; **Ruth A. David** completed a four-year term as foreign secretary; and **David E. Daniel** and **C. Paul Robinson** completed six continuous years of service as councillors, the maximum allowed under the Academy's bylaws. They were recognized in May for their distinguished service and other contributions to the NAE.

NAE Honors 2019 Russ Prize Winners

With the Fritz J. and Dolores H. Russ Prize the NAE honors outstanding individuals for significant innovation, leadership, and advances in bioengineering. Julio C. Palmaz, **Leonard Pinchuk**, Richard A. Schatz, John B. Simpson, and **Paul G. Yock** were awarded the 2019 Russ Prize "for innovations in medical devices that enable minimally invasive angioplasty treatment of advanced coronary artery disease." They were honored at a black-tie dinner on February 20 at the National Academy of Sciences in Washington. They received the awards before an audience of more than 130 guests, with NAE president **C. D. Mote, Jr.**, at the podium and M. Duane Nellis, president of Ohio University, assisting in the presentation.

Percutaneous coronary intervention (PCI), also called percutaneous transluminal coronary angioplasty (PTCA), is a minimally invasive procedure that uses a catheter to place a stent that opens up blood vessels in the heart that have been narrowed by plaque buildup. The procedure has replaced or significantly delayed the need for open heart coronary bypass surgery, and tens of millions of patients have benefited worldwide.

Julio C. Palmaz, inventor of the first FDA-approved balloon-expandable vascular stent (1990), is Ashbel Smith Professor at the University of Texas Health Science Center in San Antonio and scientific advisor of Vactronix Scientific. The Palmaz stent is on display at the Smithsonian's National Museum of American History in Washington.

Left to right: C. D. Mote, Jr., John B. Simpson, Leonard Pinchuk, Richard A. Schatz, Paul G. Yock, and M. Duane Nellis. Not present: Julio C. Palmaz.

In 1994 he and Richard Schatz created a modified coronary stent—two Palmaz stents joined by a connector—approved by the FDA as the first stent indicated for the treatment of failure of coronary balloon angioplasty. The Palmaz-Schatz stent became the gold standard for every subsequent stent submitted for FDA approval.

Leonard Pinchuk is an inventor and entrepreneur in biomedical engineering, with 128 US patents and 90 publications. He has cofounded 10 companies where his major accomplishments include invention of the Nylon 12 angioplasty balloon, helical wire stent, modular stent-graft, a drug-eluting stent (TAXUS®), several biomaterials (Bionate and poly(styrene-block-isobutylene-block-styrene) [SIBS]), a novel glaucoma tube (InnFocus MicroShunt®), and the next generation intraocular lens. He is a Distinguished Research Professor of Biomedical Engineering at the University of Miami.

Richard A. Schatz is research director of cardiovascular interventions at the Scripps Heart, Lung, and Vascular Center and director of gene and stem cell therapy. He is a recognized international expert in interventional cardiology and has published and lectured extensively. His seminal work in coronary stents spurred a revolution in the treatment of coronary artery disease—over 2 million of them are placed annually worldwide, with an immeasurable impact on relieving mortality and morbidity, improving patients' lives, and reducing healthcare costs.

John B. Simpson has helped revolutionize the field of cardiology through innovations that fundamentally altered how physicians treat cardiovascular disease. In 1981 he created a new catheter system for coronary angioplasty with an independently steerable guidewire in the central lumen of the balloon catheter, patented as the over-the-wire balloon angioplasty catheter. He now focuses his efforts on the treatment of vascular disease through the development of new technologies combined with a new approach to optical imaging.

Paul G. Yock is the Martha Meier Weiland Professor of Medicine and founding cochair of Stanford's Department of Bioengineering, with a courtesy appointment in the Department of Mechanical Engineering. He is also founder and director of the Stanford Byers Center for Biodesign. He has authored over 300 peer-reviewed publications, chapters, and editorials and two textbooks, and holds over 50 US patents. Dr. Yock is internationally known for his work in inventing, developing, and testing new devices, including the Rapid Exchange™ stenting and balloon angioplasty system, which is now the primary system in use worldwide. He also invented the fundamental approach to intravascular ultrasound imaging and founded Cardiovascular Imaging Systems (CVIS), later acquired by Boston Scientific.

Acceptance Remarks by John B. Simpson

I'm shocked that this is a reality. When I got the call I thought, 'This can't be really true.' What a thrilling event for me and all of my colleagues tonight. I want to thank the Russ family. I understand that Fritz's sister Midge is here. Can you raise your hand? Maybe all the members of the Russ family should raise their hands. Wonderful!

I did a little research on Fritz and understand that his father was a farmer and kind of shy. So was Fritz. Dolores was not so shy; she seemed to give some direction on the way things worked around the house—and maybe SRL as well.

It's mind-boggling to think about their founding the research laboratories in the era they were operating in. Today, we would call it a startup mentality or entrepreneurship, but in that era it was unprecedented. Not only to come up with a strategy for developing SRL but also then to have the vision to support a prize. Wow!

Of course I agree with Dr. Mote that this is the most impressive prize in the industry. Obviously! Who would dispute that? [laughter] That the Russes had the vision to establish the prize is amazing.

I think my colleagues would agree that the reason we can see a little farther than others is because we stand on the shoulders of giants. Fritz is one of the giants. I think in this industry everybody stands on Fritz's shoulders.

As interventional cardiologists we also stand on the shoulders of Mason Sones, who did the very first coronary angiogram, and Andreas Grüntzig, who did the first coronary balloon procedure in a human. Grüntzig, in Zurich at the time, had the courage to initiate this procedure in humans when not many of us thought it was a great idea. I heard him give a talk at Stanford and my wife, who is here, picked me up afterward and asked me, "What was that about?" I said, "This guy is going to revolutionize the treatment of vascular disease—or he's going to go to jail."

What Grüntzig was doing was radically different from what anybody else thought of: to take a small balloon catheter and put it in someone's heart and blow the balloon up and the person will get better. Now it seems obvious: You put a stent on a balloon and the stent holds the material to the side making room for more blood flow. It's sort of obvious now, but in that era it was not. We started telling surgeons that we were going to take the patients that normally would be sent for a bypass and instead use a piece of plastic with a balloon on the end of it and we are going to blow up the balloon and you don't have to operate on this patient anymore. Profoundly controversial.

Much like the controversies that Fritz might have encountered when he wanted to set up the prize. It seems to me that he would have been swimming upstream in that era.

I think Fritz's insight was that physicians by themselves and engineers by themselves might not be quite so effective. But engineers and physicians working together to solve a problem, that really is the key. If it is an important problem that we are confronting in the world today, this collaboration gives us an opportunity to do something really special.

I'm not a formally trained engineer but, when I reflect on my career, I have known how to find and rely on great engineers. I've had all my engineering training on the job, and I've had very good on-the-job training because I have worked with a lot of really really good engineers.

Among the engineers that I have worked with over the years, one of the first worked in aerospace—he designed something on the nose gear of a Grumman spacecraft or maybe a Grumman fighter jet. Then he did some things with balloon angioplasty for coronaries.

Sophisticated engineering expertise and skill sets can transfer really well between different serious problems. In this case, serious problems related to coronary artery disease, on the one hand, and nose gear on fighter jets, on the other, are surprisingly similar as they demand complex and precise engineering solutions.

I also reflect on the very first balloon angioplasty catheter that I made. I made it using electrical insulation from an F-4 Phantom fighter jet. You might say, "Insulation from the Phantom—why would you do that?" Because it was the only thing available to me at no charge; it's not like it was any great insight or anything. The Raychem Corporation had some left over and it was coincidentally the right size for human coronary arteries, so I said,

John B. Simpson

"How do I get that?" The Raychem guy said, "You can have this. We're not using it right now because all the Phantom jets are pretty much produced, so you can have some." It was free—and free in this world doesn't occur very often! So think of the Phantom jet, the electrical insulation, the right size, the plastic, the heat shrink materials—it is all derived and engineered for the electronics industry, but engineers and physicians working together took it from the fighter jet and it ended up in the human heart. It's a magical opportunity when you put this stuff together.

On behalf of my colleagues, I want to tell you how grateful we are. We are honored and humbled and so very thankful. Thank you.

NAE Regional Meeting on Cyberphysical Systems Held at University of Virginia

Twenty years ago, as president of the National Academy of Engineering, University of Virginia computer science professor **Wm. A. Wulf** launched a remarkable effort to spread the word about the importance of innovation, education. and research to the American economy. He and his wife, UVA computer science professor **Anita Jones**, established the Academy's now well-known series of regional meetings for leaders in engineering and science to share knowledge and ideas.

On April 30–May 1, this work came full circle when UVA Engineering Dean **Craig H. Benson** hosted an NAE regional meeting and symposium on cyberphysical systems, the technologies and systems at the interface of the cyber and physical worlds.

The symposium opened with a video highlighting the work of UVA Engineering's Link Lab, a collaborative space involving more than 30 affiliated faculty and 200 graduate students. In his opening remarks about the NAE's mission of service to the nation, Dr. Benson emphasized that engineers are leaders expanding the frontiers of knowledge and technology for the betterment of humanity.

NAE president **C. D. Mote, Jr.**, provided brief remarks about regional meetings as an opportunity to bring the Academy and its membership together. He said the topic of cyberphysical systems is especially important because we live in a time of accelerating change, creating global demand for engineers.

Vinton G. Cerf, vice president and chief internet evangelist for Google, gave the keynote address, "Ethics, Computer Science, and the Internet of Things." "If you come away with nothing else," he said, "please come away with a sense of deep responsibility to the society that is affected by engineering, especially the software and computer engineering that pervades our lives today."

Users expect products to just work, with intuitive interfaces and provisions for safety, reliability. and privacy, Dr. Cerf said. They also expect devices and systems of devices with interoperability and common standards. Engineers must understand that the Internet of Things is a complex ecosystem that cannot be oversimplified. The billions of devices being put to work could herald either a utopian future or a nightmare, he said, and "it is a shared responsibility to try for the former and avoid the latter."

Next was a panel discussion, "Securing the Cyberphysical Universe," led by Jack Davidson, UVA engineering computer science professor, director of the Computer Science Cybersecurity Program, and coorganizer of the UVA Cyber Innovation & Society Initiative. Panel members were Andrew Bochman, senior grid strategist, National & Homeland Security, Idaho National Laboratory; Stephanie Forrest, director of the Biodesign Center for Biocomputation, Security and Society, and professor in the School of Computing, Informatics, and Decision Sciences Engineering at Arizona State University; and **S. Shankar Sastry**, NEC Distinguished Professor of Electrical Engineering and Computer Sciences and former dean of Engineering at UC Berkeley.

Veena Misra, Distinguished Professor of Electrical and Computer Engineering at NC State University and director of the Center for Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST), a National Science Foundation-sponsored Nanosystems Engineering Research Center (NERC), delivered a presentation titled "Smart Health at the Cyber-Physical-Human Interface." She discussed opportunities in personalized health, including health monitoring that gives clinicians information about patients with chronic diseases. ASSIST researchers are developing wearable sensor systems that are self-powered and provide continuous data for patients with conditions such as asthma and arrhythmia.

George J. Pappas, the Joseph Moore Professor and chair of the Department of Electrical and Systems Engineering at the University of Pennsylvania, and member of the General Robotics, Automation, Sensing & Perception (GRASP) Laboratory and the Penn Research in Embedded Computing and Integrated Systems Engineering (PRECISE) Center, talked about "The CPS Foundations of Safe Autonomy." He reviewed progress and challenges for autonomous systems as well as research on safe mission planning for robot swarms in known environments, semantic modeling in unknown environments, and safe mission planning in unknown environments.

In his "Smart Cities for Flooding" presentation, **David Maidment**, Hussein M. Alharthy Centennial Chair in Civil Engineering at the University of Texas at Austin, outlined examples of a cyberphysical systems approach enabling communities to adopt capable, adaptable, scalable, secure systems for environmental resiliency, such as in coastal communities with extreme weather events and flooding. He also described the challenge of developing a national water model to assess hydrology on the continental scale in the United States.

Speaker presentations and videos are available at https://engineering.virginia.edu/national-academy-engineering-regional-meeting.

UT Austin Hosts NAE Regional Meeting on Disaster Analytics

Members of the National Academy of Engineering (NAE) met at the University of Texas at Austin on March 7 to examine the growing role of data analytics in natural disasters and consider how the proper application of data could be used to develop better strategies for disaster preparation and response.

Dean **Sharon L. Wood** opened the 4-hour symposium, hosted by the Cockrell School of Engineering, by welcoming regional NAE members as well as UT faculty, students, and visitors to the Mulva Auditorium in the school's Engineering Education and Research Center. "As a hub for learning and research, the Cockrell School is excited to host a discussion on how we can improve quality of life through collaboration and focused efforts on maximizing data in response to natural disasters," Dr. Wood said. "These crucial conversations are the catalyst for change as we continue to create a safer, healthier society."

NAE president **C. D. Mote, Jr.**, echoed Dr. Wood's sentiments: "Disaster analytics and recovery are extremely relevant topics, especially in Texas. It is our job as engineers and innovators to improve on existing models to create a stronger, more efficient future for our society."

Following Dr. Mote's remarks, William Tierney (NAM), chair of the Department of Population Health at the Dell Medical School, discussed the importance of establishing a more streamlined healthcare data-tracking system.

Several UT Austin faculty members then described their research from two recent catastrophic events in Texas, Hurricanes Ike (2008) and Harvey (2017). Gordon Wells, research associate in the Cockrell School's Center for Space Research, explained the importance of generating accurate, timely information during a disaster to better support response and recovery teams. Clint Dawson, professor in the Cockrell School's Department of Aerospace Engineering and Engineering Mechanics, expanded on Dr. Wells' advocacy of quality, in-the-moment analytics by adding the need for predictive storm modeling. "Data-driven modeling and analytics are crucial to predicting the impact of a potential storm," Dr. Dawson said. "We must look at the potential sociological, environmental, and economic impact of hurricanes as we continue to build and redevelop our cities and infrastructures."

The symposium continued with a presentation by **David Maidment**, professor in the Cockrell School's Department of Civil, Architectural, and Environmental Engineering, on one of UT's research gems, the *Stampede* supercomputer, which helped forecast the flow and depth of flooding during Hurricane Harvey. Amit Bhasin, director of UT Austin's Center for Transportation Research, then explored how data pulled from transportation technology are transformed into practical information that enhances public safety while maximizing efficiency and mobility. And Allan Shearer, associate dean for research and technology in UT Austin's School of Architecture, talked about increasing cities' disaster resiliency within cost constraints.

Ellen Rathje, professor in the Department of Civil, Architectural, and Environmental Engineering, closed the symposium with her presentation on the development of cloud-based tools to support the analysis, visualization, and integration of diverse data. "Every event provides an immense learning opportunity," she said, "but to actually learn from the event and improve our approach for the future, we must be able to integrate diverse datasets into a streamlined hub of information."

Texas is among the states most prone to natural disasters in both variety and severity, so engineers and researchers in the region are well positioned to capitalize on data from previous natural disasters and explore innovative ways to improve not only how we live, work, and travel but also how we can better prepare for the future.

NAE Regional Meeting on Bioengineering Hosted by Agilent

Agilent Technologies, a global leader in life sciences, diagnostics, and applied chemical markets hosted NAE's Western regional meeting and symposium at its headquarters in Santa Clara on March 28. The theme of the symposium, organized by NAE member **Darlene Solomon**, was "Bioengineering, Advancing Our World," with superb technical presentations by four of the world's leading academic researchers spanning the bioengineering discipline.

Dr. Solomon, Agilent's chief technology officer and senior vice president, welcomed attendees. She briefly described the company's commitment to technology innovation and role in expanding capabilities for analytical, life science, and clinical diagnostics laboratories around the world. She then reviewed the breadth of exciting, impactful areas that constitute the field of bioengineering and explained how the ability to measure, understand, and apply biology is advancing rapidly, enabling transformational improvement to the human condition—hence the theme for this symposium.

Next, NAE president **C. D. Mote, Jr.**, thanked Agilent for hosting the event and recognized NAE executives also in attendance: Vice President **Corale Brierley**, Executive Officer **Al Romig**, Home Secretary **Julia Phillips**, and Development Director Radka Nebesky.

Stephen Quake, Lee Otterson Professor of Bioengineering, copresident of the Chan-Zuckerberg Biohub, and professor of applied physics at Stanford University, was the first technical speaker. He described the mission and structure of the Biohub, a new nonprofit medical research organization in the Bay Area that is catalyzing basic research and technology development aimed at improving human health. The Biohub works closely with Stanford, University of California, San Francisco (UCSF), and UC Berkeley, funding nearly 100 faculty members to work on their riskiest, most exciting ideas with unrestricted gifts. It also has an internal research program on cell biology and infectious disease. Dr. Quake described the very exciting results of one of the Biohub's earliest projects: creating an atlas of the various cell types of the mouse using single-cell transcriptomic technologies developed by his lab and others.

Tejal Desai (NAM), Ernest L. Prien Professor and chair of the UCSF Department of Bioengineering and Therapeutic Sciences, presented her pivotal research in advancing fundamental insight into cellular behavior and novel pharmacologic drug delivery approaches through innovations in micro- and nanotechnology. Her work showcased how advanced engineered materials can be used to address unmet needs in therapeutic delivery, tissue regeneration, and cell therapy. By controlling material architecture at the micro- and nanoscale, materials can modify the biologic environment, leading to improved therapeutic outcomes. At UCSF, she has led the growth of engineering in the health sciences and showed how the interaction of engineers with clinicians and basic scientists can lead to innovations in health care.

After a networking break, the symposium resumed with a presentation by **Jay Keasling,** professor of chemical engineering and bioengineering at UC Berkeley, chief science and technology officer for Biosciences at the Lawrence Berkeley National Laboratory, and chief executive of the Joint BioEnergy Institute. Dr. Keasling reviewed his seminal research engineering the chemistry inside microbial cells across a variety of applications, and described his laboratory's recent work to produce valuable isoprenoid-based molecules using engineered microorganisms (isoprenoids are key ingredients in flavors, fragrances, nutraceuticals, and pharmaceuticals). His most recent work to engineer yeast to produce cannabinoids will have a large impact on the burgeoning cannabis industry by providing pure, rare, and unnatural cannabinoids without the use of cannabis.

The final speaker was **Karl Deisseroth**, D.H. Chen Professor of Bioengineering and professor of psychiatry and behavioral sciences at Stanford University. He presented his work in developing optogenetics as a research tool for controlling and mapping neurons in the brain and his application of the technology to answer fundamental behavioral questions in mice. He described his discovery, with optogenetics, of the neurons that control basic survival drives like thirst and how these cells create and change activity throughout the brain. He also discussed his discovery of the neurons that control motivation to overcome stress, in particular the cells that underlie the transition between actively meeting challenges versus passively coping with stress. Finally, he surveyed the latest advances from his hydrogel-tissue chemistry technology, which transforms biological tissues into transparent 3D structures in which proteins can be labeled, cells can be sequenced, and diagnoses made with unprecedented precision.

2019 German-American Frontiers of Engineering Held in Hamburg

The 2019 German-American Frontiers of Engineering Symposium (GAFOE) was held in Hamburg, March 21–23. The NAE partners with the Alexander von Humboldt Foundation (AvH) to organize this event, the "oldest" bilateral Frontiers of Engineering program, which was started in 1998. The symposium organizing committee was cochaired by NAE member **Dennis Discher**, Robert D. Bent Professor of Chemical and Biomolecular Engineering at the University of Pennsylvania, and Jörg Schulze, professor of electrical engineering and head of the Institute of Semiconductor Engineering at the University of Stuttgart.

Modeled on the US Frontiers of Engineering Symposium, GAFOE brings together 60 early-career engineers from German and US companies, universities, and government. The goal of the meeting is to convene emerging engineering leaders in a forum where they can learn about leading-edge developments in a range of engineering fields, thereby facilitating an interdisciplinary transfer of knowledge and methodology. In the case of the bilateral Frontiers, there is the added dimension of helping build cooperative networks of young engineers that cross national boundaries. At this year's GAFOE, the four session topics were Artificial Intelligence and Deep Learning, Electro-Mobility and Its Impact, Biomedical Optics, and Technologies for Space Exploration. The program, list of attendees, abstracts, and presentation slides can be viewed on the 2019 GAFOE website at www.naefrontiers.org.

The session on AI and deep learning highlighted interdisciplinary challenges and research advances in machine learning and AI applications. After an introduction on the current state and outlook of AI and deep learning, the first speaker described how machine learning is changing software using the example of Snorkel, an open source system that generates training data for predictive systems. This was followed by a talk on conversational assistant technologies and the AI challenges involved in building machines that can communicate with people. The third speaker focused on deep learning technologies for human and object recognition in applications ranging from aerospace to autonomous driving to virtual reality. The session concluded with a talk on machine learning for cognitive neuroscience applications.

Speakers in the session Electro-Mobility and Its Impact described impediments to the adoption of electric vehicles (EVs) such as lack of supporting infrastructure, range anxiety, and deficiencies in current battery technology. Presentations covered the current state and future vision for electric and hybrid vehicle battery systems; inductive charging of EVs; social trends that will facilitate expansion of EV use; and future EV-grid interactions that may include using EVs as services to the grid.

Biomedical optics, which uses light to examine biological tissues, is highly interdisciplinary, combining physics, engineering, and computation with biology and medicine. A major influence in the field has been the development of novel fluorescent proteins and light-activated channels that enable cells to be turned on and off with light. Neuroscience in particular has benefited from this technology. The talks in this session described basic principles and advances in near-infrared spectroscopy for measuring cerebral function, the development of genetically encoded voltage indicators—proteins that emit flashes of light when neurons are active—thereby eliminating the need for invasive electrodes, techniques based on wavefront engineering and optical time reversal to enable optical imaging of thick biological tissues, and neuroscience applications of superresolution stimulated emission depletion (STED) microscopy.

The final session, Technologies for Space Exploration, examined how the technologies that composed the symposium—artificial intelligence, optics, and electro-mobility—can be applied to exploring space, and how public and private organizations are working to solve challenges in the space industry. The first presenter, from the European Space Agency, explained the complexities of deep space missions, focusing on the Rosetta and BepiColombo missions. Next, a talk on robotic mobility described new mobility architectures that support robotic exploration of extreme terrain such as caves and lava tubes on the moon and Mars. This was followed by an overview of state-of-the-art optical instrument designs for earth observation, ranging from hyperspectral imagers (e.g., Environmental Mapping and Analysis Program, EnMAP) to Fourier transform spectrometers. The last presenter painted a future scenario of human habitation of Mars, achieved through SpaceX's Starship spacecraft and Super Heavy booster that will be capable of delivering large payloads affordably.

Alexander von Humboldt president Hans-Christian Pape, NAE president **C. D. Mote, Jr.**, and the symposium cochairs welcomed the group to the symposium. In addition to the formal sessions, a poster session preceded by flash poster talks on the first afternoon served as an icebreaker and opportunity for all participants to share information about their research and technical work. The posters were displayed throughout the meeting, which facilitated further discussion and exchange during the coffee breaks.

On the second afternoon, attendees enjoyed a boat trip on the Elbe River, exploring the port complex of Hamburg, the third busiest seaport in Europe. Sights included the Speicherstadt, or warehouse district; transshipment facilities; floating cranes; cargo ships packed high with containers; and the postmodern Elbe Philharmonic Hall. This was followed by dinner at the Restaurant Vesper in downtown Hamburg.

Funding for the meeting was provided by The Grainger Foundation, National Science Foundation, and Alexander von Humboldt Foundation. The next GAFOE meeting will be held in 2021, hosted by Oak Ridge National Laboratory.

The NAE has additional bilateral Frontiers of Engineering programs with Japan, China, and the European Union. Each brings together outstanding engineers from industry, academia, and government at a relatively early point in their careers (participants are generally within 12 years of receipt of an advanced degree). The symposia provide an opportunity for them to learn about developments, techniques, and approaches at the forefront of fields other than their own, something that has become increasingly important as engineering has become more interdisciplinary. The meetings also facilitate the establishment of contacts and collaboration among the next generation of engineering leaders.

For more information about this activity, go to www.naefrontiers.org or contact Janet Hunziker in the NAE Program Office (JHunziker@nae.edu).

EngineerGirl Announces 2019 Writing Contest Winners

The 2019 EngineerGirl writing contest asked students in grades 3–12 to write a story that celebrates engineering design and problem solving. The stories are creative works of fiction about women and girls saving the day with their wits, skill, and whatever resources they can find. Prizes were awarded to students based on grade level.

Among 3rd- to 5th-grade students, Henrietta Rasmusson, a fifth-grader at Douglas J. Regan Intermediate School in Pendleton, New York, placed first for her essay about a princess engineering her way out of a tall tower. Seventh-grader Noor Azam-Naseeruddin from Renaissance Home School Group, won first place among entries from grades 6–8 for her essay about a Hawaiian adventure. Among 9th- to 12th-graders, Audrey Rappaport, a 12th-grader at Eleanor Roosevelt High School in Bowie, Maryland, placed first for her essay about a bridge that could withstand a treacherous sea serpent.

The 2019 EngineerGirl writing contest was sponsored by Chevron Corp. and the Kenan Institute for Engineering, Technology, and Science. Awards are $500 for first place, $250 for second place, and $100 for third place. Certificates are given for honorable mentions.

All the winners and their essays are posted at https://www.engineergirl.org/2019-contest-winners.aspx.

NAE Selects Five Student Teams to Represent US at 2019 Global Grand Challenges Summit

Five teams and an alternate have been selected from more than two dozen US competitors to represent the United States in a business plan competition at the 2019 Global Grand Challenges Summit in London on September 12–18, 2019.

The summit is a collaboration of the NAE, the UK's Royal Academy of Engineering (RAEng), and the Chinese Academy of Engineering (CAE). Each academy is selecting five student teams that will propose an innovation or novel approach for addressing aspects of the theme of this year's summit, "Engineering in an Unpredictable World." The teams will convene in London to compete, and then will be reassigned onsite to mixed country teams for additional challenges.

The US teams are:

Dartmouth College

Team members: Anna Dodson, Alexandria Chen, Jack Sadoff, John Weingart, Joshua de la Cruz, and Suraj Srivatas

Mentor: Raina White

Project: The Compost Tea Project, which aims to deliver sustainable organic fertilizing solutions to low-income urban farmers who face soil nutrient deficiency but lack the space, time, and finances needed to implement traditional composting systems.

North Carolina State University

Team members: Pippin Payne, Silvana Alfieri, Grant Jordan, Rachel Figard, and Kevin Duke

Mentor: David Parish

Project: Peak Coffee Processing, a business that developed an affordable treatment process to filter wastewater into clean water and fertilizer. This will produce purified water while creating a product that economically benefits coffee producers by increasing crop yields and reducing topsoil erosion.

Oklahoma State University

Team members: Muwanika Jdiobe, Angela Peter, Christian Griffith, and Jackson Moore

Mentor: Amanda Williams

Project: An innovative technological system that increases yields and reduces input costs and waste for farmers. The system employs sensors that collect data from farms, transmitting it to a data hub for processing and communicating that information back to individual farmers.

University of California, San Diego

Team members: Ayush Sapra, Stephanie Le, Angela Joung, Hao-In Choi, Eric Richards, and Daniel Vazquez

Mentors: Mandy Bratton, Lin Hein

Project: Sulo, a business that is working with rural villagers in the Philippines to sell an affordable, reliable, and safe solar-powered lantern. The students aim to bring a reliable source of light and economic development to rural communities.

University of Southern California

Team members: Roxanna Pakkar, Celeste Goodwin, Sofia Tavella, Siena Applebaum, and Maria Camasmie

Mentor: Chris Denniston

Project: Marlink, a product that serves as the link between operators and their underwater exploration vehicles. It enables the next generation of underwater communication by pairing the robust, long-range effects of acoustic technology with the high data rates of optical technology.

University of Rochester (Alternate)

Team members: Syed Miqdad, Sara Anis, Kareem Abdel, and Afnan Ahmed

Mentor: Mark Mathias

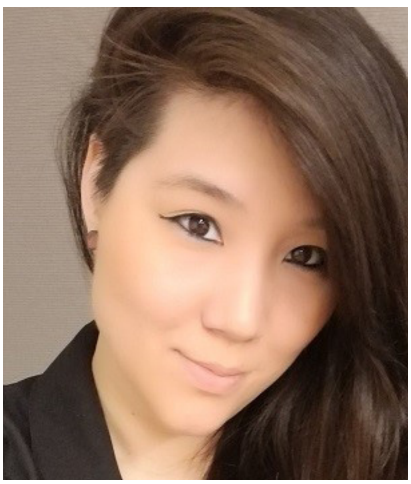
Project: EZ Water, a business that leverages locally available resources to set up a network of water shops run by micropreneurs who filter water locally without electricity and serve the needs of people in low-income communities. The team will represent the United States if any of the above teams drops out.

In an effort to ensure that solutions address the most pressing issues facing targeted populations, the NAE teams participated in a version of the National Science Foundation's I-Corps program. Teams were trained to identify, access, and interview key members of the ecosystems who are directly impacted by the problems they are attempting to solve. Teams interviewed numerous "customers" and in doing so came to a deeper understanding of the specific challenges they must address.

The 2019 Global Grand Challenges Summit will be broadcast worldwide, with satellite events on every continent, creating a truly global effort in addressing global grand challenges through engineering. The summit was inspired by the NAE 14 Grand Challenges for Engineering.

New Staff

KIM CASE joined the staff as senior membership associate on February 11. She brings a range of database management and web technology skills to support and coordinate the annual nomination, evaluation, and election of members and foreign members. She will also manage the logistical planning details for election committee meetings and events. Kim is a graduate of Rutgers University, where she majored in political science and was a competitive swimmer. In her free time, she enjoys running and playing with her Frenchie. Kim is in NAS 304 and can be reached at 202.334.2263 or KCase@nae.edu.



Kim Case

KIM MIDDLETON joined the staff as senior membership associate on February 18. She is the logistics coordinator for the regional meetings and, for the annual meeting, will coordinate the guest tours and assist with publications, catering, and the dinner dance. She comes to us from the NAS executive office, where she was a membership associate. Kim is a graduate of the City University at Brooklyn College, where she majored in political science. In her free time, Kim is involved in the activities and education of her three children. She is in NAS 309 and can be reached at 202.334.2223 or KMiddleton@nae.edu.

Kim Middleton

Calendar of Meetings and Events

June 10	NAE Audit Committee Meeting
June 18	NAE Finance Committee Meeting
June 19	Engagement of Engineering Societies in Undergraduate Engineering Education: 2019 ASEE Annual Conference—Distinguished Lecture Tampa, Florida
June 24	NAE Deans' Roundtable on Linking Academic Engineering Research and Defense Basic Science
July 30–August 1	NAE Council Meeting Woods Hole, Massachusetts
September 16–18	2019 Global Grand Challenges Summit London
September 25–27	US Frontiers of Engineering North Charleston, South Carolina
October 4–5	NAE Council Meeting
October 5–7	**NAE Annual Meeting**

All meetings are held in National Academies facilities in Washington, DC, unless otherwise noted.

2019 Annual Meeting Forum

"No single space project," said President Kennedy in May 1961, "will be more exciting, or more impressive to mankind, or more important…and none will be so difficult or expensive to accomplish."

In December 1968 Apollo 8 lifted off for a lunar mission and, just months later, in July 1969, the first human steps on the moon dramatically changed the course of engineering achievements. New sciences, technological applications, and business practices emerged from this rigorous systems engineering effort that, 50 years later, continues to fuel the imagination and ambition of countless engineers. Engineering has enabled the International Space Station and the investigation of once far-fetched ideas such as permanent colonies on the moon and human missions to Mars and beyond.

At this year's NAE annual meeting, the plenary speakers and technical forum panelists will reflect on this inspiring trajectory of ingenuity, achievements, and lessons, starting from the Apollo mission—why it still resonates and remains relevant and meaningful for current exploration and discovery. In addition to reviewing technical achievements and social implications, the speakers will discuss the nature of modern global collaboration and competition as well as implications for future exploration, workforce development, and public engagement.

In Memoriam

MIHRAN S. AGBABIAN, 95, professor emeritus of civil engineering, University of Southern California, died February 13, 2019. Dr. Agbabian was elected in 1982 for contributions in the application of advanced methods of applied mechanics to structural design, and contributions in the field of structural response to blast and shock and the reduction of seismic hazards to existing structures.

JOHN F. AHEARNE, 84, retired executive director, Sigma Xi, The Scientific Research Society, died March 12, 2019. Dr. Ahearne was elected in 1996 for leadership in energy policy and the safety and regulation of nuclear power.

ZHORES I. ALFEROV, 88, rector, Nanotechnology Research and Education Center RAS, St. Petersburg Academic University, and vice president, Russian Academy of Sciences, died March 1, 2019. Dr. Alferov was elected a foreign member in 1990 for pioneering contributions to the theory and technology of compound semiconductor heterostructure devices and materials.

PAUL A. ALLAIRE, 80, former chair and CEO, Xerox Corporation, died February 24, 2019. Mr. Allaire was elected in 1996 for advancing electronic document technology and for leadership in promoting education, diversity, and industrial competitiveness.

EGON BALAS, 96, University Professor and Thomas Lord Professor of Operations Research, Tepper School of Business, Carnegie Mellon University, died March 18, 2019. Dr. Balas was elected in 2006 for contributions to integer programming and its applications to the scheduling and planning of industrial facilities.

ELWYN BERLEKAMP, 78, Elwyn & Jennifer Berlekamp Foundation, died April 9, 2019. Dr. Berlekamp was elected in 1977 for research in information and coding theory, and their applications to communications and computer memory systems.

BEN H. CAUDLE, 95, professor emeritus, University of Texas at Austin, died February 6, 2019. Dr. Caudle was elected in 1988 for outstanding contributions to petroleum engineering education and research and for setting high standards of professionalism.

SUNLIN CHOU, 72, retired senior vice president and general manager, Technology and Manufacturing Group, Intel Corporation, died December 5, 2018. Dr. Chou was elected in 2004 for pioneering work on silicon processes resulting in 35 years of improvements in accordance with Moore's law.

JACQUES S. GANSLER, 84, chair and CEO, Argis Group, died December 4, 2018. Mr. Gansler was elected in 2002 for public and private leadership in the US Department of Defense and major contributions in teaching missile guidance and control systems.

RALPH S. GENS, 94, retired chief engineer, Bonneville Power Administration, died January 3, 2019. Mr. Gens was elected in 1983 for contributions to the advancement of electric power transmission technology through creative engineering accomplishments and management leadership of research and development.

GEOFFREY F. HEWITT, 84, emeritus professor of chemical engineering, Imperial College London, died January 19, 2019. Dr. Hewitt was elected a foreign member in 1998 for fundamental contributions to multiphase flow, especially annular gas/liquid flow, and translating research results into industrial practice.

EDWARD E. HOOD JR., 88, retired vice chair and executive officer, General Electric Company, died February 3, 2019. Mr. Hood was elected in 1980 for contributions to the advancement of aircraft engines in efficiency, reliability, and environmental compatibility and the application of the engines to the commercial airlines industry.

WILLIAM A. HUSTRULID, 78, Hustrulid Mining Services, died April 24, 2019. Dr. Hustrulid was elected in 2007 for contributions to the theory and practice of geomechanics in the design of safe and efficient underground mining systems.

MILAN M. JOVANOVIC, 66, senior vice president, Research and Development, Delta Electronics (Americas) Ltd., died October 9, 2018. Dr. Jovanovic was elected in 2015 for efficiency improvements of AC-DC power supplies in information technology systems.

ROBERT P. KENNEDY, 79, consulting engineer, RPK Structural Mechanics Consulting, died December 30, 2018. Dr. Kennedy was elected in 1991 for developing design procedures for civil and mechanical structures to resist seismic and other extreme loading conditions.

JAMES U. LEMKE, 89, founder and chief scientist, Achates Power Inc., died February 21, 2019. Dr. Lemke was elected in 1988 for lifelong leadership in magnetic recording theory and practice, including both engineering design and materials science.

JAMES D. LIVINGSTON, 88, retired senior lecturer, Massachusetts Institute of Technology, died May 7, 2019. Dr. Livingston was elected in 1994 for developing the relationship between microstructure and the superconducting, ferromagnetic, and mechanical properties of metals and alloys.

ROBERT D. LORENZ, 72, Elmer and Janet Kaiser Chair and Consolidated Papers Professor of Controls Engineering, University of Wisconsin–Madison, died January 27, 2019. Dr. Lorenz was elected in 2019 for contributions to modeling and control of cross-coupled electromechanical systems for high-performance electric machines and drives.

GEORGE K. MUELLNER, 75, vice chair of the board, Aerospace Corporation, died February 11, 2019. Mr. Muellner was elected in 2015 for leadership in the research, design, and development of advanced air and space vehicles.

NILS J. NILSSON, 86, professor of computer science emeritus, Stanford University, died April 23, 2019. Dr. Nilsson was elected in 2018 for foundational contributions to robotics, heuristic search, planning, and machine learning.

SUBBIAH RAMALINGAM, 83, professor emeritus, University of Minnesota, Minneapolis, died February 9, 2019. Dr. Ramalingam was elected in 1998 for machining and tool-life theories, coating-design algorithms, and invention of novel automation sensors and steered-arc coating technology.

ROBERT H. REDIKER, 94, retired senior vice president, Advanced Research and Development, Cynosure Inc., died December 29, 2018. Dr. Rediker was elected in 1989 for pioneering contributions and leadership in constructing semiconductor compound light emitters and lasers.

KENNETH F. REINSCHMIDT, 80, emeritus professor of civil engineering, Texas A&M University, died December 30, 2018. Dr. Reinschmidt was elected in 1991 for innovative development of productive uses for computers in plant and building design, construction, and operation.

RICHARD SCHERRER, 99, died December 21, 2018. Mr. Scherrer was elected in 2010 for his pioneering work on revolutionary aircraft designs with extremely low radar cross sections that led to the F117A stealth fighter.

MASANOBU SHINOZUKA, 87, UCI Distinguished Professor, University of California, Irvine, died November 5, 2018. Dr. Shinozuka was elected in 1978 for contributions to random vibration and related applications to safety and reliability of structures.

ROBERT M. STEIN, 82, consultant and former vice president and officer, Raytheon Company, died April 2, 2019. Mr. Stein was elected in 2019 for contributions to electronic systems for national security applications.

FRED STERZER, 89, president, MMTC, Inc., died December 2, 2018. Dr. Sterzer was elected in 1983 for continuing significant contributions in development of advanced microwave devices and for motivating researchers in the forefront of microwave technology.

WILLIAM F. TINNEY, 97, independent consultant, died April 14, 2019. Mr. Tinney was elected in 1998 for initiating sparse-matrix technology in electrical engineering and contributions to power-system computer applications.

WALTER J. WEBER JR., 84, Gordon M. Fair and Earnest Boyce Distinguished University Professor, University of Michigan, died October 18, 2018. Dr. Weber was elected in 1985 for expanding wastewater treatment technology by analyzing, evaluating, and clarifying physio-chemical principles of solute separation.

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