FEATURE

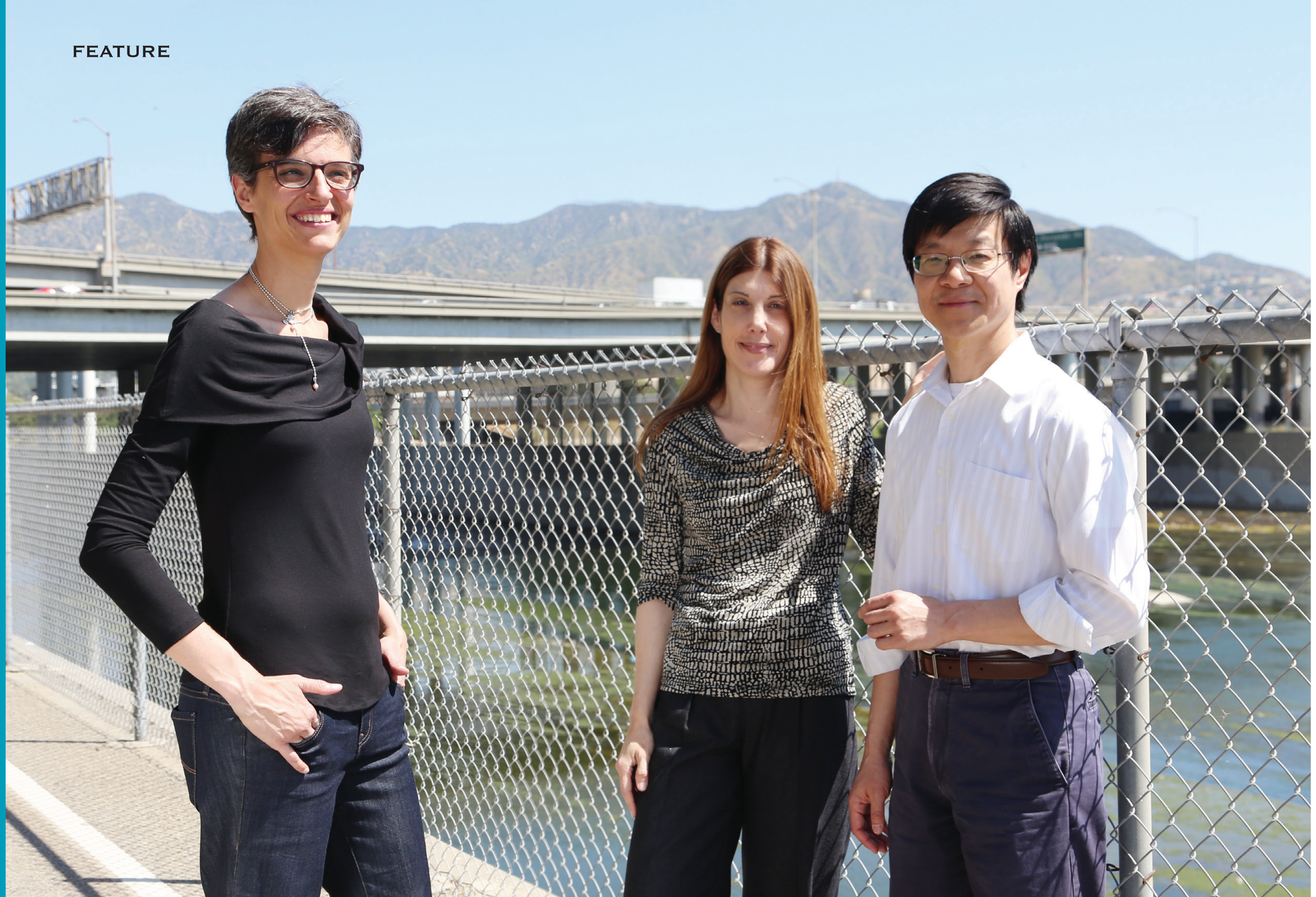
Making Megacities Resilient

(Starting with Los Angeles)

Resilience is the capacity to endure and recover from stress, to bend and not break. Caltech engineers and scientists have a long track record of studying the resilience of materials and structures, from geological strata to material alloys. The Division of Engineering and Applied Science (EAS) has decided to further build on this body of research by identifying "resilient megacities" as one of five future research thrusts.

ENGenious brought three faculty members from different EAS disciplines together for a discussion about attempts to quantify and improve the resilience of megacities and to create—specifically in the context of Los Angeles—design strategies and tools that can make megacities more resilient without ignoring other important factors, such as sustainability.

Megacities are a trademark of the twenty-first century, as more and more activities, structures, and people concentrate in relatively few spots around the world. Over 30 cities worldwide now have populations that



Chiara Daraio, Domniki Asimaki, and Steven Low by the Los Angeles River

surpass 10 million people, including Greater Los Angeles, with more than 18 million.

Even in the developed world, however, these concentrated urban areas are plagued with problems of infrastructure arising from their original planning, which was intended to cover the needs of a city population 100 years ago and did not include strategic plans for expansion, monitoring, retrofit, or repairs to the network infrastructure. Deeper problems thus loom for the future. This is particularly true for megacities located in active earthquake zones, like Los Angeles, but nearby oceans and mountain and rivers can also be threats. Such places may be plagued with problems of infrastructure—critical systems of transportation, communication, power, and water, oil, and gas distribution are prone to interruption, and more major disruption would have serious consequences.

"Despite the advancements in construction methods and materials," says Professor of Mechanical and Civil Engineering Domniki Asimaki, "people are more vulnerable to hazards today than they were before because of population concentration, reliance on data and electricity, as well as the coupling of all infrastructure systems that comprise modern urban centers."

In Los Angeles, the realization has been dawning that with new engineering and communication tools, at least some of these worries can be abated. This dialogue, focused on making Los Angeles not just a megacity but a smarter megacity, is beginning to broaden in important ways. The city of Los Angeles has a resilience task force, headed by a chief resilience officer, urban planner Marissa Aho. Aho is at work developing a Resilience Assessment Overlay, seeking to reduce the vulnerability of the entire immense Los Angeles complex—underground, offshore, electrical and digital, structures and systems—and make it both more resilient and more sustainable, in the context of public planning and expenditure.

"The Overlay," according to Asimaki, "is an effort to prioritize spending for public infrastructure (pipelines, buildings, communication network components) so that in the occurrence of the next big earthquake, human and economic loss will be minimized, and the city will have improved its capability to pick up and start functioning again." Her definition of resilience, in terms of megacity planning and growth, is ambitious but vital: "A resilient system is a system of systems of people and infrastructure and administrations that responds fast during extreme events and recovers rapidly, economically, health-wise and with minimal loss of life."

Asimaki has long been working on a critical area of megacity stress. Her field is geotechnical engineering, computational mechanics, and engineering seismology, dealing with complicated problems involved in estimating the impact of potential earthquakes. The geological formations subject to quakes are very heterogeneous. Even within quite short distances—tens of meters—their physical properties, such as stiffness and strength, can be different. And

Downtown Los Angeles

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Domniki Asimaki, *Professor of Mechanical and Civil Engineering*

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Steven H. Low, *Professor of Computer Science and Electrical Engineering*

consequently, the force transmitted from a quake varies significantly according to the specific composition of material at its focus, the stiffness and strength of the material, and whether it yields gradually to the forces or suddenly breaks. Asimaki has been using her techniques for probing earthquake effects on shallow geologic features, and the impact of these effects on the built environment, to create a resilience atlas of Greater Los Angeles.

Asimaki's work has been part of the evolution of the field of earthquake engineering, which, she says, "was born here at Caltech, out of seismology." It then grew into an independent field with an emphasis on the study of buildings and bridges and tunnels, and the two fields uncoupled. "Over the years, we lost the common vocabulary," she explains, "and now we're at a point of coming back together and looking at expanding from the individual structure to systems. We're back working together out of necessity to define the hazards and quantify the risks and the impact on the infrastructure systems on the scale of entire cities."

Professor of Mechanical Engineering and Applied Physics Chiara Daraio is also involved in this reunification of the fields. She teaches about resilience of materials in her undergraduate mechanics class (ME 12c). "There's a quantitative definition for modulus of resilience in materials, which is the energy absorbed by a material upon elastic deformation," she says. "The higher the resilience of a material, the more it can recover from large deformations without permanent damage." Similarly, a resilient megacity should be able to recover from increasing stresses, like population growth, environmental or climate changes, and unexpected events, without permanently fracturing the city's infrastructure or damaging its quality of living.

Daraio and her research group study the response of materials to external stimuli, like stresses and temperature, and apply these findings to create new, optimally resilient materials and sensing devices that could be used to monitor infrastructures.

Other members of the EAS faculty are at work on such problems, as well. Professor of Computer Science and Electrical Engineering Steven Low specializes in management of networks, both power systems distributing electricity and the Internet and other communication services. These networks are vulnerable to disruption, from hardware destruction to cyber-physical attacks or simple congestion, even in the absence of earthquakes or other major stress events.

"A city comprises interacting systems of critical infrastructures, organizations, communities, and people," says Low. "A resilient megacity not only minimizes the impact of a disruption to human life, the economy, and the infrastructures but must also heal itself. Our current infrastructures are often developed organically without such foresight, and, as a result, a failure in one infrastructure can cascade into another. For instance, an earthquake can bring down part of the power grid, which may cause a disruption of the water distribution system, shutting down pumped hydro energy storage and potentially causing a blackout or brownout. Failures can be quickly amplified throughout the megacity."

The earthquake situation applies, almost by definition, to events compressed into a narrow time scale. But the researchers say that resilience can be a valuable goal even at much, much longer time scales—over the life of cities.

Therefore, as Daraio explains, aging infrastructure such as crumbling roads, collapsing bridges, leaking pipelines, and failing water systems must be part of resilience planning. "There must be either redundancy or some alternative plan ready—a flexible emergency response–type plan that effectively reacts to local failures in these systems," she says.

Low notes that one key to developing this type of resiliency is an evolving understanding of how to coordinate or unify the disparate elements involved. "In the past, different components were more separated," he says, but "today the connectivity among data, operations, controls, and optimization is more developed. So not immediately but conceivably, the whole complex system can act like one when it is needed." He is not talking about a city that is all centrally controlled or centrally managed: "The resiliency structure can be distributed yet coordinated so that the entire system can react as a coherent whole."

Creating such a distributed response system requires consideration of elements that are not strictly engineering concerns, says Daraio. "Engineering can improve the building technology and controls of infrastructures, for example, by introducing new materials and distributed sensor networks that actively monitor performances," she explains. "But acquiring data alone is not enough, as the data must be used to coordinate a response to the events monitored. To be able to properly respond, a combination of engineering and social sciences is necessary. Translating the infrastructure performance of a system delivering a service involves policy and community well-being, which go hand in hand with economic and social factors. Along with concerns for sustainability."

Asimaki provides an example of how different kinds of vulnerabilities demand different resilience postures. "Let's say an earthquake happens," she says. "There's debris and then reconstruction, so there will be an additional carbon footprint to build new buildings, which harms the environment." But this is partly due to poor preparation: "If the performance of the structure were better and there wasn't catastrophic collapse, we would not have to do so much to disrupt the natural environment following the disaster."

The reality of developing resilience can be much more complicated, as is now being seen in the Sacramento delta and on the coast. "We are trying to protect the waterfront and its human inhabitants from floods or sea-level rise, so we create additional manmade structures to protect the coastal cities from hurricanes or floods or from sea level rise," Asimaki says. "But by doing this, we increase the hazard of floods, and we harm the wetlands, all of which have potential negative impacts."

It's a very complex problem. She goes on: "We can't just increase the number of performance sensors or just make the control systems more efficient. There is a dependency on constructing and over-densifying population into megacities. This is further complicated because we cannot stop the growth of cities, so we have to think about the problem in a completely different way. Making individual structures resilient to earthquakes is not adequate if it's not followed by a resilience plan of infrastructure systems that impact the performance of groups of such structures, a resilience plan that accounts for the interdependency of these systems, a mitigation and emergency response plan that spans entire urban centers, and an education and outreach plan to teach the public how to prepare and respond when the Big One happens."

Low's specialty, power and networks, involves somewhat different tradeoffs on resilience and sustainability, including cases where the two goals coincide—when an emphasis on resilience can also be beneficial for sustainability. Giant centralized power plants, either fossil fueled or nuclear or hydro, that still generate about two-thirds of our electricity, are almost by definition barriers to resilience. If one plant is knocked out, the whole system is disturbed, and if two are knocked out, stability of the whole system will be threatened. "But new systems of distributed wind and solar power with backed-up batteries can distribute the vulnerability," he points out, "creating both a more sustainable and a more resilient generation infrastructure." For instance, Low says, "with local generation and storage, blackouts can be avoided in many places for weeks and months," even after severe damages. "There may be areas where resilience and sustainability conflict, but this is where I think we can achieve both." By understanding such conflicts in advance, he adds, adjustments can be made: "If we connect all sorts of data, then we can understand a lot more about the city as a whole and how the different pieces interact."

It's key, the researchers say, that the government of Los Angeles and its surroundings now seem aware of the critical need to grow in a better way. The establishment of an office of resilience and a resilience officer may not seem revolutionary, but these are steps in the right direction, integrating social science and engineering planning in essential ways.

Moving forward, the engineering faculty agree that Caltech is uniquely equipped to help make Southern California a prototype of smart urban planning. Caltech's interdisciplinary environment and its low barriers to collaboration allow them to be innovative and disruptive in their approaches. Their focus on fundamentals and insistence on rigor will allow these researchers to help tackle the most complex challenges that the planners of resilient megacities of the future must overcome.

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It's critical, then, that "Los Angeles, with its resilience task force and other initiatives, is the first city in the U.S. that's making resilience a design goal," adds Asimaki. This, combined with the strategic decision of the EAS Division to focus on this area of research, has made this the perfect time and place to explore our city's capacity to endure and recover from stress—to bend and not break. ENG

Domniki Asimaki is Professor of Mechanical and Civil Engineering. Chiara Daraio is Professor of Mechanical Engineering and Applied Physics. Steven H. Low is Professor of Computer Science and Electrical Engineering.