When the Big One Hits

More than 1,100 kilometers long, the San Andreas fault separates the Pacific and North American tectonic plates. The fault marches straight down this photo of the Carrizo Plain National Monument, which is about 150 kilometers north of Los Angeles. Because the plain is an arid environment, there isn't much erosion, and the fault scarp remains visible.

Seismologists say the Big One could strike any day. To better prepare for a potential catastrophe, researchers are simulating how buildings respond to earthquakes and helping to conduct the biggest earthquake drill ever.

On November 13, 2008, at 10 a.m., the San Andreas fault jolted Bombay Beach, a small town on the shores of the Salton Sea, 100 kilometers southeast of Palm Springs. In a split second, the two sides of the fault slid 13 meters. Like a zipper unzipping, the rupture shot 300 kilometers northwestward along the fault at more than three kilometers per second, sending seismic ripples across Southern California. The 7.8-magnitude earthquake rocked the Los Angeles metropolitan area, shaking the basin for nearly a minute. Buildings collapsed and dozens of city blocks went up in flames. With water lines broken, there wasn't enough water to fight the conflagration. 1,800 people died and 50,000 were injured. The quake caused more than $200 billion in damage. Strong

The Great Southern California ShakeOut!!

By Marcus Y. Woo

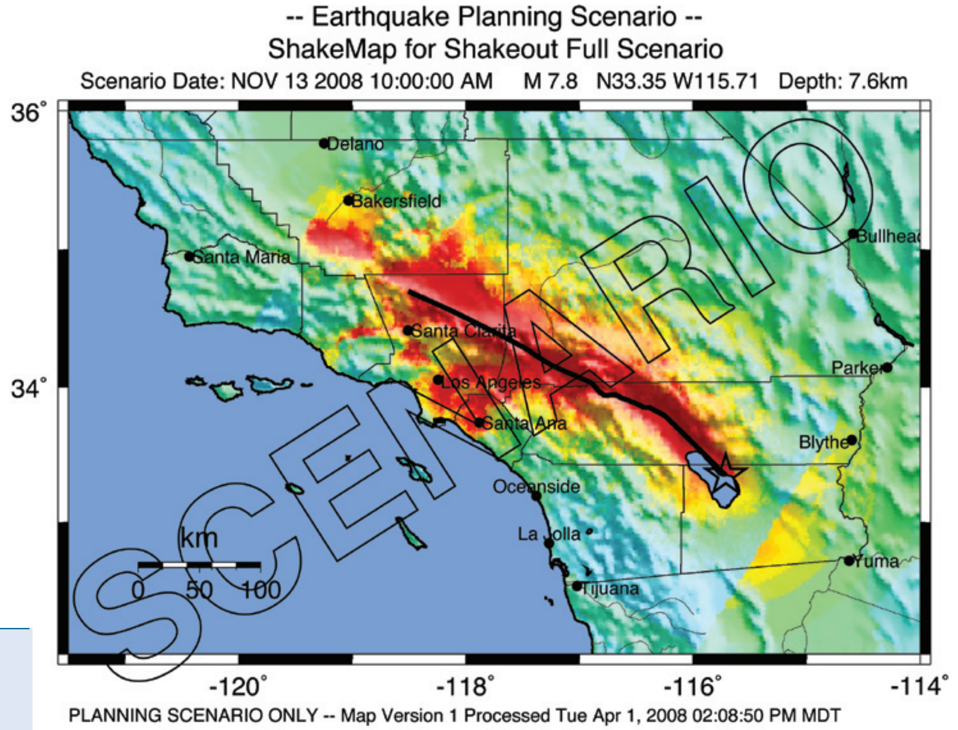
aftershocks—some bigger than the last big quake in the region, the 6.7-magnitude Northridge quake in 1994 that killed 57 people—struck often and hard. The catastrophe would affect businesses and lives for years to come.

Fortunately, of course, this never really happened. The scenario described above was the plot line of the Great Southern California ShakeOut, the biggest and most comprehensive earthquake drill ever. The ShakeOut scenario was a strong quake, but neither a worst-case scenario nor an improbable one. In fact, there's a 99 percent chance an earthquake of 6.7 magnitude or greater will hit California in the next 30 years, according to a recent report by the United States Geological Survey.

Chances are, that quake will be on the southern portion of the San Andreas fault, where the Pacific Plate slides along the North American Plate at the blistering pace of a few centimeters per year. Although the word "plate" may connote breakable dinnerware, tectonic plates are not entirely rigid. While the rest of the Pacific Plate gently moves northward, friction keeps the edge along the fault locked to the North American side. Over decades, the strain builds. Eventually the fault ruptures and the two plates slip, covering in one catastrophic moment the distance traveled by the rest of the plate in centuries. Although the fault runs along the north side of the San Gabriel Mountains—40 kilometers from Los Angeles at its closest approach—the reverberations are felt for hundreds of miles. Seismologists think that a big quake on the southern San Andreas happens as frequently as every couple hundred years or so, and the last massive one—a 7.9 temblor known as the Fort Tejon quake—hit on January 9, 1857. Although seismologists can't predict earthquakes—they emphasize that the Great ShakeOut was not a prediction but a "what if" scenario—they warn that California is due for the Big One.

The ShakeOut, however, was more than a glorified version of a duck-and-cover drill, familiar these days in earthquake country. The goal was to prepare Southern California for the next big earthquake with the most realistic scenario possible, one based on the best science available. The drill relied on detailed computer simulations, and from those simulations, more than 300 experts derived specific emergency situations such as damaged water, power, oil, and railroad lines, widespread fires, and broken telecommunication links. They quantified the impact on the infrastructure, the economy, and individual lives.

As some seismologists like to say, "Earthquakes don't kill people. Buildings kill people." Because Southern California was sparsely populated in 1857 and tall buildings were still a century away, the Fort Tejon quake claimed only two lives. But today, hundreds of buildings tens of stories high scatter the region, and the ability of these structures to hold up to earthquakes will be



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

This ShakeMap shows the extent of the simulated earthquake's shaking. Although scientists can't predict when and how future earthquakes will strike, they can assign a size and location to a hypothetical earthquake and predict its effects.

Nearly 70,000 people died in Sichuan, and thousands of them were children who were crushed under poorly constructed schools. “When you lose children,” Krishnan remarks, “you lose a whole generation of people.”

the difference between life and death. In fact, half of the fatalities from the ShakeOut scenario were from collapsing buildings.

Assistant Professor of Civil Engineering and Geophysics Swaminathan Krishnan (PhD ’03) shakes buildings on a computer to see whether they will survive. For his PhD thesis, he wrote software that models how every element of a building would respond to jostling. A couple of years ago, he started collaborating with Jeroen Tromp of Princeton, who was then Caltech’s McMillan Professor of Geophysics and director of the Seismological Laboratory. Tromp’s area of expertise was simulating earthquakes with computers, perfectly meshing with Krishnan’s work. Together, they created the first “end-to-end” simulations, modeling a complete scenario from the “bottom end” of a seismic rupture and regionwide earthquake, to the “top end” of an individual shaking building. According to Tromp, their collaboration marked the first time seismologists had joined forces with civil engineers to analyze how structures resist—or succumb to—earthquakes.

Building codes in California are rewritten periodically so that they’re as up to date as possible, but because data detailing buildings’ performance in large earthquakes are hard to come by, simulations are crucial in determining whether the codes are up to snuff. As the magnitude-7.9 Sichuan quake last May tragically illustrated, collapsing buildings can be catastrophic. Nearly 70,000 people died in Sichuan, and thousands of them were children who were crushed under poorly constructed schools. “When you lose children,” Krishnan remarks, “you lose a whole generation of people.” Sichuan was a sobering reminder of an earthquake’s devastation. As an engineer, Krishnan says he relishes the intellectual challenge of calculating structural responses to earthquakes. But ultimately, his goal is to save lives.

TIME TO SHAKE THINGS UP

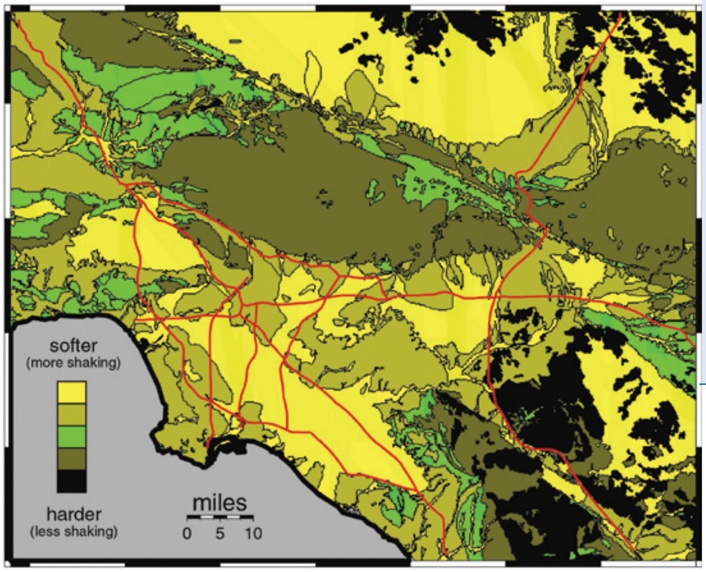
Krishnan and Tromp’s initial study looked at that 1857 earthquake, one of the biggest in U.S. history. Although most of the damage centered on the region’s most populated area—Fort Tejon, an army outpost about 120 kilometers north of Los Angeles—shaking was felt throughout the Los Angeles basin and as far away as Las Vegas. The *Los Angeles Star* reported that the Los Angeles River sloshed back and forth, Krishnan says, and the researchers deduced that for such a large body of water to slosh so much, the shaking must have been pretty intense and must have lasted from one to two minutes—a long time compared with the Northridge quake, which shook for only 10 to 20 seconds.

The sloshing also implied that the 1857 quake had seismic waves with relatively long periods, ranging from two to eight seconds. These long-period motions are especially worrisome because they target tall buildings. Buildings are like pendulums—a longer pendulum swings more slowly than a shorter one. When the seismic wave period matches the building’s natural resonant frequency, it will sway—and possibly break and collapse. (For example, the nine-story Millikan Library in the center of campus is sensitive to a period of 0.85 seconds.) The Fort Tejon earthquake would have shaken buildings in the range of 15 to 20 stories the most, had they existed. Buildings of a few stories would have been largely undisturbed, much like small leaves gently riding wind-driven swells in a lake. Damage was pretty severe where there was anything to damage—part of the Mission San Buenaventura’s tower in Ventura collapsed, for example. Today, with hundreds of buildings 15 or more stories high scattered across the region, long-period motion could have devastating consequences.

We can’t escape low-frequency rocking—it’s a characteristic of our geology. Los Angeles sits in sedimentary basins that formed 15 million years ago after the surrounding mountains rose. Over time, the sea and rivers carried sediments into the basins, creating a thick, soft layer 10 kilometers deep on which Los Angeles and its suburbs have been built. During an earthquake, the seismic waves bounce back and forth between the hard walls of the surrounding mountains, like water sloshing in a bathtub.

Tromp’s work builds on dramatic advances in computer hardware and numerical techniques over the past decade. The earthquake simulation starts with what’s called a source model, which details where the rupture started, how fast it moved, and how far it went. There weren’t any seismo-

The Sichuan earthquake in May 2008 destroyed many schools, including this middle school in the town of Yingxiu.



This map of the Los Angeles region shows the softness of near-surface rocks and sediments. Data for image courtesy of Chris Wills, California Division of Mines and Geology.

graphs in 1857, so the researchers, including Krishnan, Tromp, Chen Ji (PhD '02) of UC Santa Barbara, and Dimitri Komatitsch of the University of Pau in France, turned to measurements of the 7.9-magnitude earthquake in 2002 that shook Denali in Alaska. The Denali fault system is similar to that of the San Andreas, and would serve as a reliable proxy. The investigators made a source model and incorporated it into the key component of an accurate earthquake simulation: a three-dimensional model of Southern California's geology, created to determine how fast different kinds of seismic waves would propagate.

This earth model, as it's called, uses data from actual earthquakes. Just as a gentle tap helps you find the juiciest watermelon, seismic waves traveling through the ground betray the earth's hidden structure. Even the smallest quake provides valuable information, and the Southern California Seismic Network (SCSN) constantly monitors the earth's rumbles and murmurs. Run by Caltech and the USGS, the network consists of 350 sensors scattered from the U.S.-Mexico border through San Luis Obispo and Big Pine. Analyzing a wave's arrival times at each of the SCSN's far-flung stations reveals occurrences such as subtle changes in density, which governs wave speed.

Although the network is one of the largest and most sophisticated in the world, it's still limited. Sensors don't blanket every square meter of the region, constraining the model's resolution. Short-period wavelengths are shorter than the size of the mesh, so researchers can only reliably simulate long-period shaking—waves with periods greater than about two seconds.

Short-period shaking quickly dies out as the waves propagate away from the fault, so neglecting them is fine when simulating bigger earthquakes, such as the Fort Tejon quake or the ShakeOut scenario, in which long-period motions dominate a large swath of land. But close to the fault rupture, the short-period trembling is powerful—and, as we've seen, causes more damage to smaller buildings, such as homes. Southern California has plenty of faults that lie right underneath our houses. One is the Newport-Inglewood fault, which stretches 75 kilometers from Culver City to Newport Beach, and last ruptured in the 6.3-magnitude Long Beach quake in 1933. Another is the Sierra Madre fault that lies north of Pasadena. Near Caltech are the Hollywood Hills fault, Eagle Rock fault, and the Raymond fault, which goes from San Marino to Arcadia and passes about two kilometers south of the Caltech Seismology Lab. Prudence would require simulating short-period motions as well, meaning a denser seismic network is needed to increase the earth model's resolution. But conventional seismic stations are expensive and require dedicated data lines to the central processing system. So Caltech seismologists are developing a cheaper, portable sensor network that can be used not only in Los Angeles, but also in places with weaker infrastructure such as Mexico, Peru, and China (see box next page).

To ensure their simulations were accurate, the researchers used the Northridge quake to test their simulation. Krishnan's team took half of the seismograph recordings to reconstruct the rupture and develop a source model. They then recreated the Northridge quake and compared the synthetic waves with the other half of the data, and indeed, the simulations matched well.

Then, armed with the Denali source model, the earth model, and 200 processors, the researchers simulated two earthquakes. Both were of magnitude 7.9 and ruptured 290 kilometers of the San Andreas. The first, however, was similar to the 1857 one, in which the rupture started at Parkfield in central California and went southward toward Los Angeles. In the second, the rupture started just north of Los Angeles, and continued northward to Parkfield. In the first case, the seismic energy was aimed at the heart of the city; in the second, it was flipped around. So how would this change affect our buildings?

A New Seismic Network

From left to right: Simulated seismic waves from the Chino Hills earthquake that hit on July 29, 2008. The wave field as sampled with the current network density shows little coherence. The predicted field sampled with 1,000 stations, however, shows clear wavefronts.

A new seismic network may be coming soon to a computer near you. A group of Caltech seismologists led by Robert Clayton, professor of geophysics and acting director of the Seismological Laboratory; Thomas Heaton, professor of engineering seismology and director of the Earthquake Engineering Research Laboratory; Mani Chandy, Ramo Professor and professor of computer science; and Monica Kohler, a visiting associate in civil engineering, are developing a new, low-cost, portable earthquake-measuring device that may help mitigate the impacts of catastrophic quakes—and possibly save lives.

The quarter-sized gadget, which attaches to computers through a USB port, would be part of a global network of seismic sensors that provides real-time data on the level of shaking after an earthquake. For example, the instrument could tell people immediately whether it's safe to go back inside their homes or schools after a quake. Additionally, units close to the epicenter can provide a warning to more distant sites a few seconds before a coming temblor.

Because they're cheap and small, the new sensors can also be easily deployed to bolster the Southern California Seismic Network (SCSN), the 350-unit system now scattered across the Southland. An improved, denser network—the target being a total of one thousand units—will allow scientists to deepen their understanding of earthquakes and build more precise earth models that are crucial for seismic simulations.

Run by Caltech and the USGS, the SCSN is not just an academic enterprise. It has proven invaluable for helping direct emergency response to earthquakes. For example, the SCSN produces "ShakeMaps" that detail where and how much the ground shook. Once computers in the Seismological Laboratory detect an earthquake—which can be as small as 2.5 in magnitude—they automatically produce a map and post it online, mere minutes after the quake. (To see ShakeMaps, go to http://earthquake.usgs.gov/eqcenter/shakemap/).

The current network's seismometers are connected by dedicated links to Caltech's Seismological Laboratory and are high-precision sensors, but they are difficult to install and maintain, and cost $100,000 each. The USB device costs only tens of dollars and relies on its host computer for power, communication, and some processing capability. (The researchers are also exploring the use of a larger, self-contained unit the size of a lunch pail. This $3,000 device, which only needs a power supply and wireless Internet, is designed to be placed in secure environments such as fire stations.)

The tiny unit, which employs the same technology as a car's airbag triggering mechanism, is less sensitive than the $100,000 seismometer, but its price and portability is unparalleled. In quiet times, the sensors phone home once a day, so scientists can keep tabs on the network. If an earthquake strikes, the unit logs in to report the peak magnitude, duration, and frequency of the shaking.

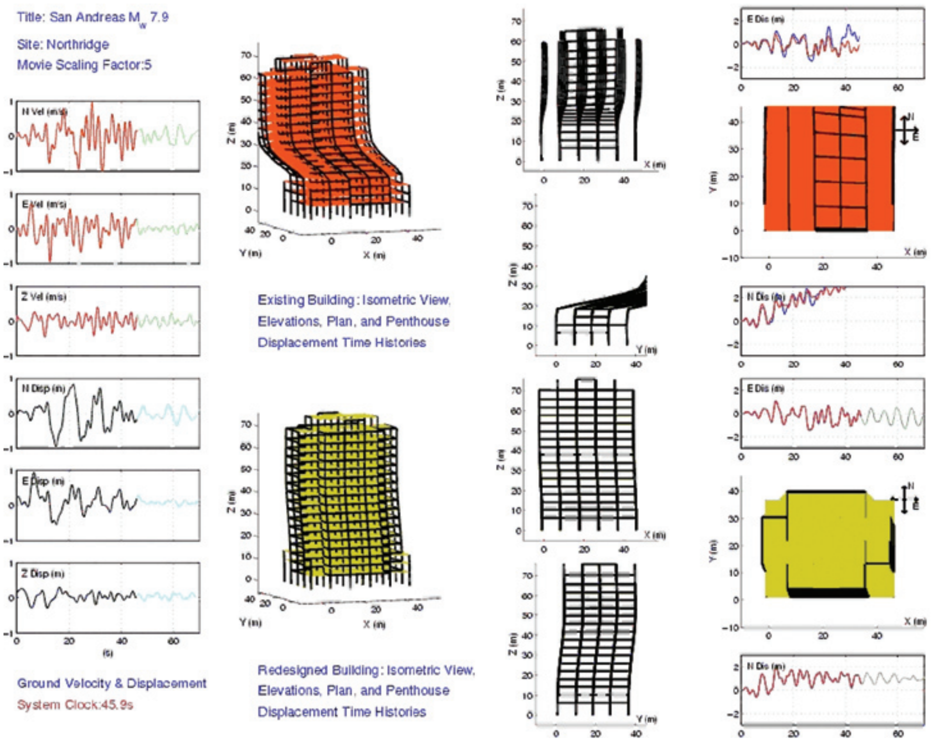
The researchers are starting a two-year pilot program to place the smaller units in 28 schools around Pasadena. The ultimate goal is to deploy a million of these gadgets around the world—in particular, in places such as Mexico, China, and Peru. Those countries lack the infrastructure to easily build a seismic network. But, with Internet cafés everywhere, those places are easily reached via cyberspace and are perfect for the new sensors, Clayton says.

BROKEN BUILDINGS

The 1994 Northridge earthquake caused more than $40 billion in damage and revealed the weaknesses of so-called steel-moment-frame buildings. Moment frames consist of a grid of beams and columns welded together, and are designed to resist the horizontal motion caused by rocking ground. Engineers thought the connections that joined the beams and columns were ductile, stretchy enough to resist being pulled apart. But Northridge showed that this wasn't the case. Cracks were found along the welds, which were more brittle than engineers thought. Also, the welding process itself inadvertently created points susceptible to stress, making the problem worse. Furthermore, many of the damaged buildings were built before 1976, when less was known about structural resistance to earthquakes. The lessons learned from Northridge led to updated building codes in 1997. But Los Angeles hasn't had a big quake since then—so are the new specifications adequate?

To find out, Krishnan's team modeled a building that was damaged in the Northridge quake—an 18-story steel structure built in 1984 on Canoga Avenue in the Woodland Hills district of the San Fernando Valley. This building has been the subject of numerous studies and is relatively well understood. The researchers placed 636 identical copies of that building about 3.5 kilometers apart on a grid covering the Los Angeles metropolitan area from Huntington Beach to Simi Valley. They then shook each building with the

This snapshot of a movie shows Krishnan's simulation of a building's response to the Northridge earthquake. The existing structure designed with pre-1997 building codes is on the top half. The redesigned building with updated codes is on the bottom. The graphs in the far-right column show how much the building is twisted. The blue lines represent the displacement of one corner of the roof, and the red lines depict the opposite corner. Their divergence represents the twisting motion. There is so much twisting that the pre-1997 building collapses.



specific seismic waves that the earthquake simulations dictated for that particular location, and calculated how every beam, column, and joint of the building would move. The researchers made two grids—one with the existing buildings designed according to 1982 codes, and one with a redesigned buildings with the updated codes.

The simulations showed that, indeed, the new buildings fared better. In the first earthquake—the one headed toward Los Angeles—many of the connections fractured in the pre-Northridge designs. In the San Fernando Valley, more than 25 percent of them failed in each building. In areas such as West Los Angeles, Santa Monica, Inglewood, Alhambra, Anaheim, and Seal Beach, 20 percent of the connections fractured. In downtown Los Angeles and Beverly Hills, the fracture fraction was 10 percent.

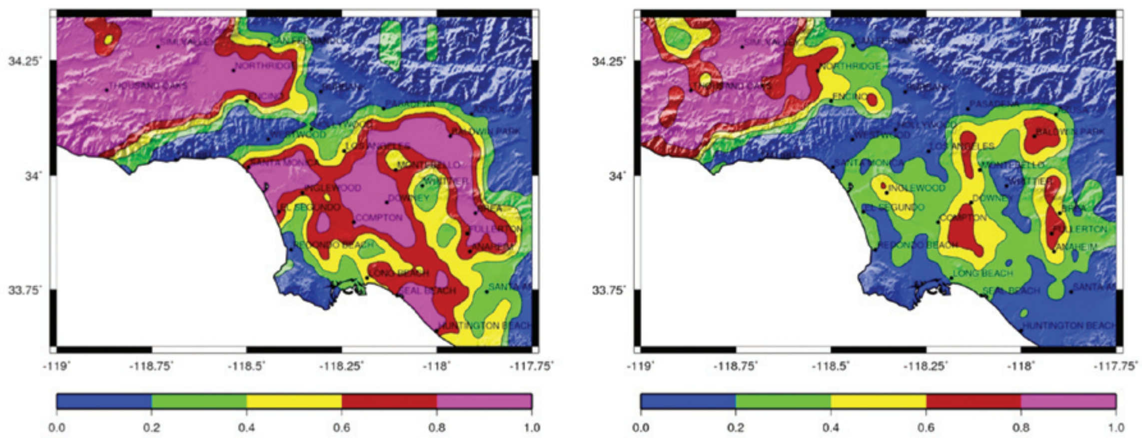
While the percentage of fractured connections is telling, the key measurement is the interstory drift ratio (IDR), which is defined as the difference in displacement between the top and bottom of a story, divided by the story's height. The higher the value, the more the ceiling is offset from the floor, and the more the building is bent out of shape. The Federal Emergency Management Agency (FEMA) sets three levels of damage based on IDR values. Different from the colored-tag system used for assessing buildings after a post-earthquake inspection, the IDR-based levels are used for more quantitative analyses. The category with the least amount of damage is called "immediate occupancy," defined as having IDR values of 0.007 or lower. These buildings may need some minor repairs, but as the name implies, they are safe to live and work in. Buildings with IDRs up to 0.025 are labeled "life safe," meaning they've suffered significant damage but aren't about to collapse. FEMA considers buildings with IDRs up to 0.05 at risk of collapse—these buildings may still be upright, but they're on the verge of coming down. If the IDR is greater than 0.05, the building is literally bent out of shape, and would likely be given red tags after a post-earthquake inspection, meaning the building's off-limits.

In the simulations, the highest IDR values in buildings were way above FEMA's collapse prevention level of 0.05—they were more than 0.1—in the San Fernando Valley, Santa Monica, and the areas surrounding Baldwin Park, West Los Angeles, Norwalk, and Seal Beach. Tall buildings in these areas would most likely become rubble. In downtown Los Angeles and Beverly Hills, the IDR values hit 0.05. Furthermore, the earthquake caused the most damage to the lower and middle thirds of the buildings, increasing the risk of the structures pancaking on themselves.

The new buildings fared better, as you would hope. None of the ones in the Los Angeles basin had IDRs of greater than 0.05. Although these buildings would most likely be closed down because of permanent tilts, they probably won't fall on people. Still, simulations struck San Fernando Valley hard, causing most buildings there to have IDRs 0.1 or higher. But this doesn't mean that the San Fernando Valley is doomed. The damage depends strongly on the specific earthquake, as shown dramatically in the second simulation when the rupture was flipped around and traveled from south to north.

This second scenario produced far less ground shaking throughout the region. In the case of the old buildings, the San Fernando Valley saw only 3 to 7 percent of its connections fracture. In Santa Monica and El Segundo, about 4 to 5 percent were fractured. There was minimal fracturing elsewhere.

The lessons learned from Northridge led to updated building codes in 1997. But Los Angeles hasn't had a big quake since then—so are the new specifications adequate?



Krishnan's and Muto's estimated costs of damaged and collapsed buildings from the ShakeOut. Buildings at places with a value of 1.0 (magenta) will have to be replaced. A value of 0.1 (blue) means the damage will be 10 percent of the replacement cost (estimated to be $72 million). The map on the left is based on the pre-1997 building codes. The one on the right is based on the updated designs.

The highest IDR values were 0.03—heavily damaged but not in danger of collapse—in the San Fernando Valley, Santa Monica, El Segundo, and Baldwin Park. The new buildings were just slightly better, experiencing IDRs of at most 0.03. Most were around 0.01. "If scenario one occurs, it may collapse some of our buildings," Krishnan says. "But if scenario two occurs, it may not be all that bad, so let's pray for scenario two."

Of course, this analysis was based on just two specific building designs and two specific earthquake scenarios, and extracting broader implications is difficult. "Should we do anything about issues that this study raises?" Krishnan says. "Well, should you put money in the stock market? Should you put it in mutual funds or high-risk stocks? It's the same question. It depends on the risk-averseness of society at large." At the very least, this work shows that reliable simulations combining seismology and civil engineering are possible, a prelude to more sophisticated studies in the future. One immediate application could be to test the safety of an important new building—a new hospital in downtown Los Angeles, for instance.

Krishnan's group is now looking at the collapse susceptibility of other designs, such as so-called braced-frame buildings, which feature diagonal struts for extra support. Ultimately, he hopes to run simulations of many different structures in various earthquake scenarios and be able to provide city planners and officials with quantified estimates of damage and risk for any building in Los Angeles.

The researchers also want to make their simulations even more realistic by including the interactions between the building and the soil it sits on. Earthquakes loosen the top layer of soil, which changes the behavior of the building, adding another level of complexity. Geophysicist Tromp wants to push the collaboration between engineers and seismologists to tackle these problems. "This is where the next frontier lies," he says.

THE POTENTIAL FOR CATASTROPHE

But analyzing the impacts of earthquakes doesn't stop at crooked buildings. These "end-to-end" simulations run from seismic source to shaken structures. But the true "end" of the analysis could be pushed farther—examining not only physical damage, but also economic loss. So Krishnan, research scientist Matthew Muto (MS '01, PhD '07); James Beck (PhD '79), professor of engineering and applied science; and Judith Mitrani-Reiser (PhD '07) of Johns Hopkins have taken the first steps to derive the probabilistic costs of repairing—or replacing—the buildings that were damaged in the simulations.

First, they looked at a previous study done on 12 structures damaged during the 1995 earthquake in Kobe, Japan. (At a magnitude of 6.9, Kobe was roughly comparable to Northridge). Using this data, they figured out the probability that the entire building would need to be replaced or repaired, and how much that would cost. They used the IDR values as a measure of how likely it was that the buildings would be damaged, with higher values meaning a greater chance that the building would have to be replaced.

For buildings that could be repaired, Muto and Krishnan looked at the components—drywall partitions, electrical and plumbing systems, sprinklers, and elevators, for example. Drawing from empirical data taken by other engineers on how these various parts hold up to stresses, they calculated IDR-dependent probabilities and costs for repair or replacement.

Muto emphasizes that this is a prototype study, based on a handful of specific buildings. But again, this kind of analysis will pave the way for more comprehensive studies, incorporating multiple earthquake scenarios and many different building types.

Which brings us back to the ShakeOut scenario. Krishnan and Muto applied their methods to estimate how many midsized, steel buildings would collapse under the 7.8-magnitude ShakeOut earthquake. They made a grid of 784 sites, each containing three buildings—the same pre- and post-1997 18-story office buildings from their earlier work, and a 19-story L-shaped structure designed according to 1997 building codes. The ShakeOut exercise also involved another team from UCLA that studied the response of reinforced-concrete buildings.

There are hundreds of buildings in the Los Angeles metro area more than 10 stories high, and by combining a census of these buildings with the simulation results, Muto and Krishnan recommended that the Shake-

Out drill should be conducted by assuming that eight tall buildings would collapse, 16 would be red-tagged—meaning that they're on the verge of collapsing and are unsafe to enter—24 buildings would be damaged enough to kill people, and 32 buildings would have visible damage resulting in injuries.

The ShakeOut event was designed to shake the public out of its complacency and remind everyone that the Big One is inevitable. If we do nothing to prepare ourselves, the consequences will be dire. But even researchers like Muto were surprised at how powerful the shaking was. And the results of their simulations were indeed serious. "The potential for catastrophe is pretty intimidating," Muto says.

DEAD TECHERS WALKING

On the Caltech campus, the drill was equally serious. When the clock struck 10 a.m. on that warm Thursday in November, the entire campus, along with millions of participants in eight counties—5.3 million people registered—ducked, covered, and held on. Throughout the day, the Institute practiced responding to various emergencies, such as power outages, fires, chemical spills, and casualties. Outside Beckman Auditorium and the Caltech Y, a few dozen people—mainly undergraduates—lay on the ground, groaning in pain. Many were covered in blood, courtesy of friends in Caltech's theater arts program. Each "victim" had specific injuries for emergency personnel to diagnose and treat. Some had minor cuts, some had bones sticking out of their flesh, and others were dying. Some were trapped under rubble—made from cardboard—and had to be pulled out.

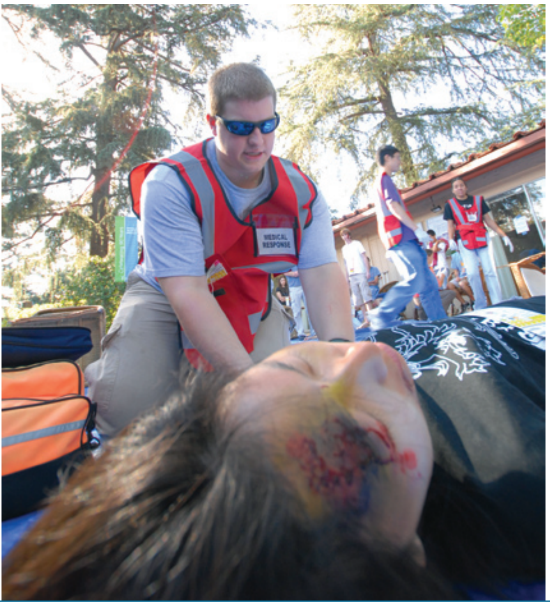
The emergency responders were from the Caltech Health Advocate Program, which trains undergraduates in first aid, treating routine health problems, peer counseling, and how to respond to crises. Volunteers and current trainees took on the role of the injured. Overall, the exercise went well, says Marshall Grinstead, a junior, who suffered a minor scrape on his head as one of the "walking wounded." He didn't get one of the "cool injuries" that would have allowed him to ride the cart to the tennis courts by the gym, where the injured were treated. But, he adds, maybe that was better than playing dead. "People who were dead got really bored." Tired of lying there in the heat, some of them got up and walked around.

Individuals, local governments, schools, and businesses all participated in the ShakeOut, says the USGS's Ken Hudnut, a Caltech visiting associate in geophysics. In fact, there were more participants than the 5.3 million who registered, he says. "We clearly got a tremendous response from the public," he says. "It feels pretty good." Hudnut was involved in the entire effort, helping with the simulations and with the emergency response. "I've been doing earthquake research my whole career," he says, "and I feel like I haven't made as much of a societal impact until now."

As part of the drill, officials were able to test various emergency response systems, such as satellite phones. One of the biggest successes, according to Hudnut, was the interdisciplinary nature of the ShakeOut, which brought together sociologists, economists, seismologists, engineers, and even artists—the Art Center College of Design in Pasadena helped produce a video that depicted the catastrophic impacts of the ShakeOut.

"In the past, when we talk about the Big One on the San Andreas, we were not very specific," Hudnut says. An ambiguous danger doesn't always provoke the response a specific scenario would. But with the ShakeOut effort and studies like those of Krishnan's, the potential impacts have become clear and specific, and hopefully people have taken the message to heart. California governor Arnold Schwarzenegger, to his credit, was particularly interested in Krishnan and Muto's work, says Hudnut, who briefed the governor for the ShakeOut.

The next time we duck, cover, and hold on, it might not be a drill, and the collapsed buildings may be real. Seismologists say the stretch of the San Andreas south of Parkfield feels a big quake every 150 years or so. The Fort Tejon quake shook the northern segment in 1857. The southern part—where the ShakeOut rupture happened—last felt a quake more than 300 yearsr ago. For Southern California, the Big One's due. e&s



As part of the ShakeOut drill at Caltech, student volunteers pretend to be injured while other volunteers tend to them in front of the Caltech Y.