A Solution for Carbon Dioxide Overload

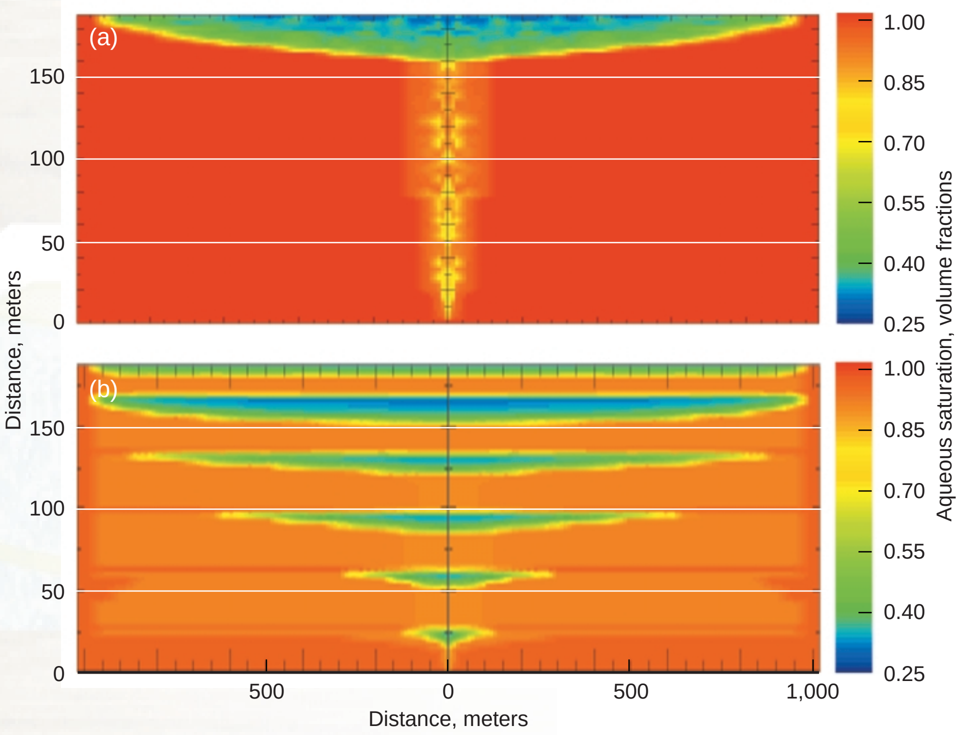
MORE carbon dioxide is making its way into our atmosphere as we burn fossil fuels and deforest tropical lands. Most experts agree that increased emissions of greenhouse gases—especially carbon dioxide—are responsible for an overall warming of our planet over the last 150 years.

In 1991, Norway became the first country to impose a federal tax on atmospheric CO_2 emissions from combustion-based point sources such as coal-fired power plants. Shortly thereafter, this tax—$55 per ton of CO_2—was extended to include emissions associated with offshore oil and gas production. The day is not far off when other countries, possibly including the U.S., will follow Norway's lead, thus creating a strong financial incentive to develop strategies for safe disposal of CO_2 waste streams.

One such strategy is to capture excess CO_2 and inject it underground, where it will remain sequestered from the atmosphere for thousands of years. Geochemist James W. Johnson is heading a Livermore team that is developing criteria for identifying subsurface geologic formations that could be used for CO_2 sequestration. "Our work is part of a long-term Department of Energy effort to identify optimal sites for sequestering CO_2," says Johnson.

Although CO_2 injection is a technique commonly used for enhancing the recovery of oil, large-scale injection for the sole purpose of isolating CO_2 from the atmosphere is occurring at just one place today: the offshore Sleipner facility, owned and operated by Statoil, Norway's state oil company. Located beneath the Norwegian sector of the North Sea, the extensive Sleipner West natural gas field is characterized by a high (9 percent) concentration of CO_2, well above the 2.5-percent limit imposed by European export specifications. Statoil strips excess CO_2 from the recovered gas in a tower on its offshore production platform before exporting the gas to the European community. Injecting the captured CO_2 into a confined aquifer—800 meters below the seabed and 2,500 meters above the Sleipner West hydrocarbon reservoir—results in no tax on Statoil for its atmospheric emissions.

Since 1996, Statoil has injected about a million tons of CO_2 per year and saved $55 million per year in taxes. The injection facility cost just $80 million to construct, and its operation accounts for less than 1 percent of overall production costs. At Sleipner, geologic sequestration has proved to be an



Sequestration performance depends on the geology of the proposed sequestration site. (a) In an aquifer with no shale layers, the CO_2 plume rises quickly to the aquifer caprock, where it migrates laterally beneath this impermeable seal. (b) When shale units are present, they effectively retard the plume's vertical migration while promoting its lateral extension, thus enhancing the effects of solubility and mineral trapping.

environmentally sound and financially prudent disposal option for excess CO_2.

Starting with simulations of CO_2 injection at the Sleipner site, Johnson and his collaborators, Carl Steefel and John Nitao, are developing a general modeling capability for analyzing CO_2 sequestration in geologic formations. This Livermore team is uniquely qualified to forge this capability, given their experience in developing an internationally recognized suite of reactive transport simulators (GIMRT, NUFT), supporting geochemical software (SUPCRT92), and thermodynamic-kinetic databases (GEMBOCHS). Using this integrated toolbox, they have begun to identify the geochemical, hydrologic, and structural constraints on successful geologic CO_2 sequestration. Eventually, they will correlate these constraints with the characteristics of potential geologic formations, rank their overall sequestration performance based on this correlation, and thus identify optimal injection sites.

Modeling a Dynamic System

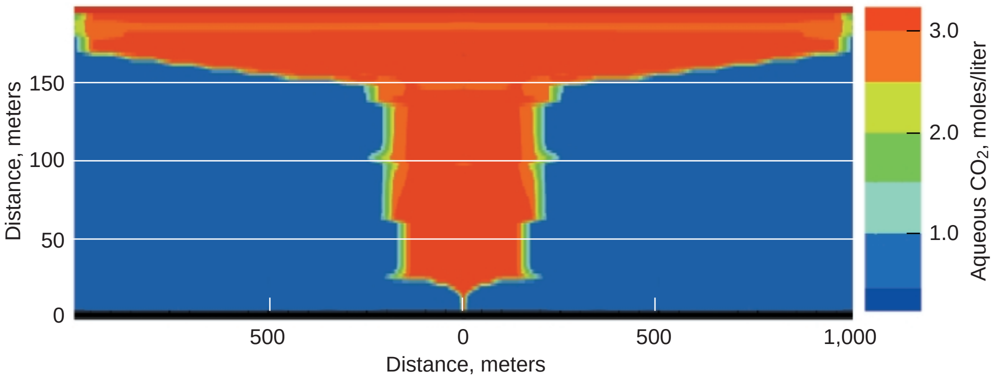
Reactive transport modeling integrates the geochemical, hydrological, and mechanical processes that characterize dynamic geologic systems. These processes, which include chemical reactions, fluid flow, heat transfer, and mechanical stress and strain, are interdependent and must be modeled simultaneously to simulate the true behavior of geologic systems. Simultaneous modeling was not possible for complex geologic systems until the advent of massively parallel supercomputers. Now, Johnson's team is producing the first-ever reactive transport simulations of CO_2 injection and sequestration within geologic formations.

Their initial Sleipner simulations examine what happens to CO_2 after it is pumped into its watery grave. At Sleipner, the storage formation is a highly porous, fluid-saturated sandstone aquifer, sealed at both the top and bottom by thick, relatively impermeable shale. The CO_2 moves through the formation via several migration processes and at the same time is trapped by various sequestration processes. The CO_2 migrates by displacing ambient water, with which it is largely immiscible, and by rising relative to this water, owing to its lower density. It also moves faster than the ambient fluid because of its lower viscosity. As the CO_2 plume migrates, some of it may react with formation minerals to precipitate carbonates (mineral trapping), some dissolves into the formation waters (solubility trapping), and some may eventually be isolated within anticlinal structures bound by the shale cap (hydrodynamic trapping).

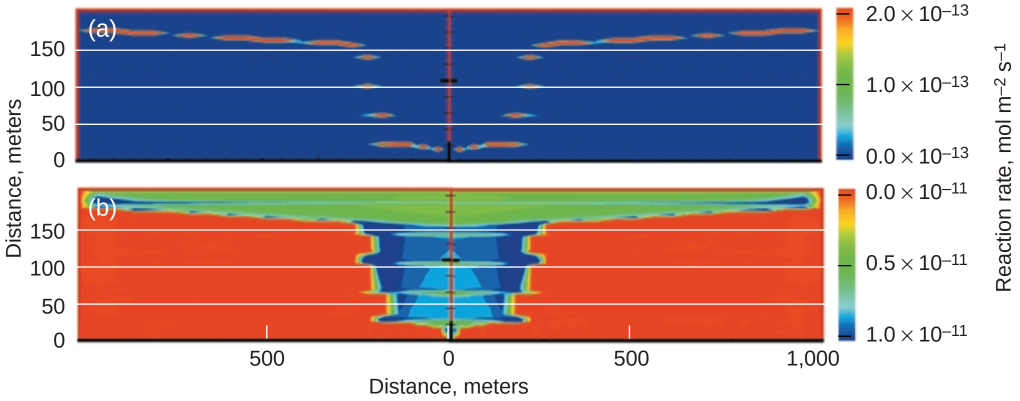
Understanding the relative effectiveness of these competing migration and sequestration processes is the key to identifying sites that will provide optimal sequestration performance. Reactive transport modeling represents a unique capability for quantifying this balance of processes.

First Results

The results of preliminary, two-dimensional NUFT and GIMRT simulations of CO_2 injection at Sleipner are shown in the three figures here, which illustrate the relative effectiveness of various sequestration processes after one year of injection. The figure on p. 20 illustrates the profound dependence of the CO_2 plume's location on the absence or presence of thin shale barriers within the aquifer. Without these layers, the CO_2 plume rises quickly to the aquifer caprock, where it then migrates laterally beneath this impermeable seal. When low-permeability shale units are present, as they are at Sleipner, they effectively retard the plume's vertical migration while promoting its lateral extension. The shale layers not only delay the arrival of the CO_2 plume at the caprock but also increase tremendously the volumetric extent of plume interaction with the aquifer and thus the potential for solubility and mineral trapping.



When shale layers are present, aqueous CO_2 concentrations are as high as 3 moles per liter within a large part of the aquifer. The overall distribution indicates that solubility trapping has sequestered about 3 percent of the injected CO_2 after 1 year, a small but measurable amount.



When shale layers are present, mineral trapping is limited to (a) minor calcite precipitation, which occurs at the expense of (b) plagioclase dissolution. Both are dependent on the effects of CO_2 solubility. Mineral trapping has sequestered less than 1 percent of the injected CO_2 after 1 year, a small but measurable amount.

The figure on p. 21 shows the spatial distribution of aqueous CO_2 concentrations when shale layers are present. It indicates that about 3 percent of the total injected CO_2 has dissolved into the ambient formation waters. Thus, solubility trapping represents a small but measurable contribution to aggregate sequestration.

The contribution of mineral trapping is also small but measurable. Precipitation of carbonates requires the presence of appropriate elements within formation minerals. In this Sleipner simulation, only a small concentration of one such element (calcium) is present in a single formation mineral (plagioclase), also of small concentration. Hence, mineral trapping is limited to minor calcite precipitation at the expense of plagioclase dissolution—a very slow process relative to solubility trapping. After 1 year, calcite precipitation has sequestered less than 1 percent of the injected CO_2.

In this preliminary 1-year simulation, solubility and mineral sequestration account for less than 4 percent of the injected CO_2. However, the relative effectiveness of solubility and especially of mineral trapping may be significantly increased over longer time frames within formations whose ambient fluid composition and mineralogy are different from Sleipner's. Johnson is quick to note, "Our research is first-cut reactive transport modeling of the complex CO_2 injection–sequestration problem." Other potentially significant effects will be evaluated in future work.

A Collaboration Begins

The preliminary reactive-transport simulations of CO_2 injection that Johnson's team carried out at Sleipner used site-specific technical data available in the public domain, but these data are insufficient for further detailed modeling efforts. Livermore recently initiated a collaboration with the International Energy Association (IEA), which coordinates research and development and monitoring of the Saline Aquifer CO_2 Storage (SACS) project at Sleipner. As part of the collaboration, IEA–SACS will supply Livermore with additional Sleipner data, which will permit more highly resolved simulations. These improved models will yield new insights into the current injection process and perhaps ways to improve sequestration performance at Sleipner.

For Livermore and the Department of Energy, obtaining more data for the unique Sleipner CO_2 sequestration project—and developing a general modeling capability based on Sleipner simulations—is invaluable. The problem of excess CO_2 must be solved, geologic sequestration represents a potentially promising solution, and reactive-transport modeling provides a unique way to identify optimal geologic formations for sequestration in the U.S.

—Katie Walter

Key Words: carbon dioxide sequestration, reactive transport modeling.

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Preparing for Strong Earthquakes

NOTHING like a mighty earthquake demonstrates the power of nature. People who live through one remember it forever.

California's Loma Prieta and Northridge earthquakes were disastrous, but experts warn that more and possibly bigger earthquakes threaten the state. We're powerless to prevent them, but we can prepare. That is just what the University of California (UC) is doing, with the help of the Campus Earthquake Program (CEP), a partnership of Lawrence Livermore National Laboratory and seven UC campuses. The CEP is helping UC prepare for large earthquakes by determining what can be expected at specific sites on various campuses.

Livermore's François Heuze, a geotechnical engineer in the Energy and Environment Directorate, initiated and leads the CEP. Heuze explains, "Campus structures were damaged from the moderate Loma Prieta and Northridge earthquakes. In larger tremors, University campuses could suffer loss of life and serious damage."

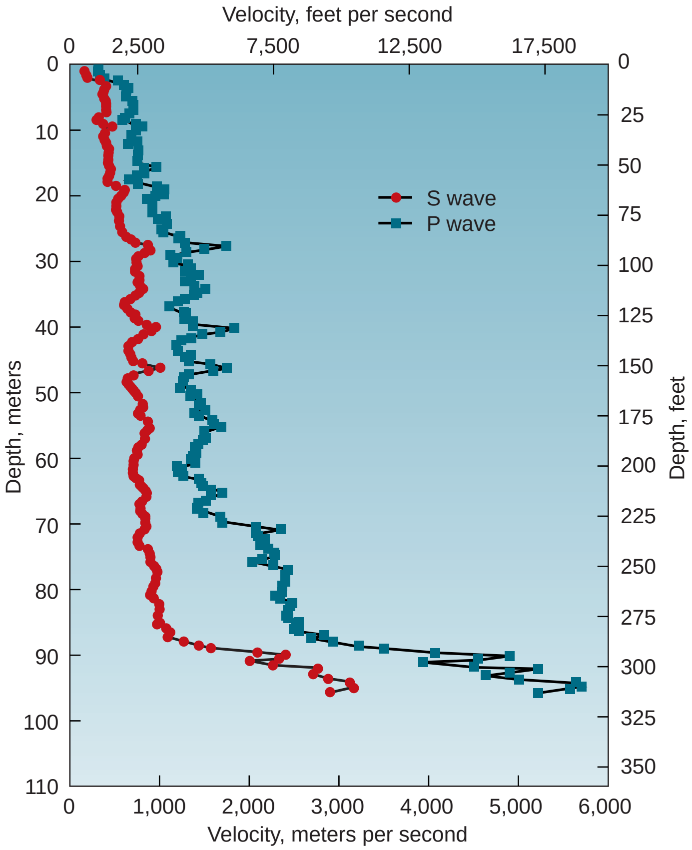
The work has been funded under the Campus–Laboratory Collaboration Program of the UC Office of the President. It has also received funding from the campuses that had sites evaluated as well as from Lawrence Livermore's University Relations Program.

From Research to Reality

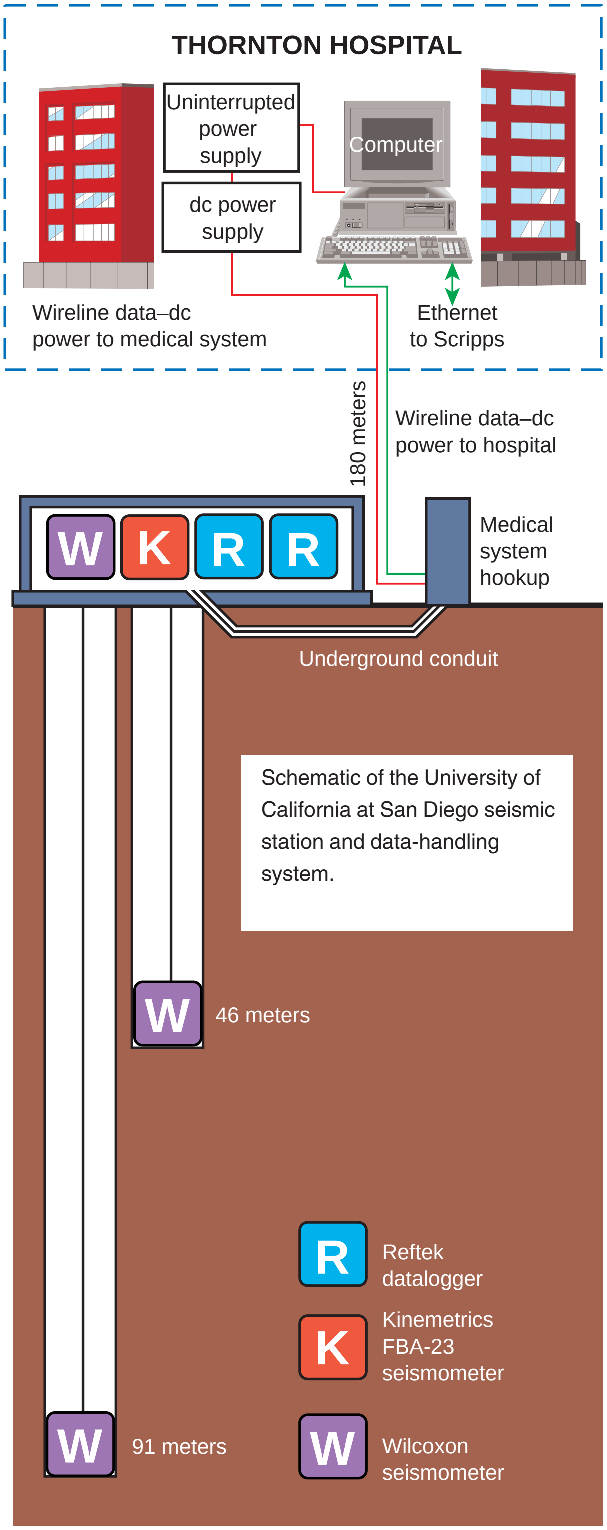
The Campus Earthquake Program had its genesis as a research project in Livermore's Laboratory Directed Research and Development (LDRD) Program in 1991. In this project, started by the Engineering Directorate's Gerry Goudreau, Laboratory seismologists and geotechnical engineers used site-specific records from small earthquakes to predict strong ground motions at those same sites during large earthquakes. Then structural engineers on the team used these strong-motion estimates to calculate the response of specific structures, such as the Dumbarton Bridge crossing San Francisco Bay (see *Energy & Technology Review*, September–October 1993, pp. 7–17).

With LDRD results in hand, Heuze met with UC officials to determine their interest in conducting similar studies at the campuses. At the time, UC's seismic policy was quite brief. "It basically said that if you had any earthquake concerns, you should call a structural engineer," recalls Heuze. UC campuses at Riverside, San Diego, and Santa Barbara expressed interest in acquiring additional information about specific sites on their campuses.

About the same time, the UC Office of the President initiated the Campus–Laboratory Collaboration program to encourage cooperative research between the national laboratories and the campuses. Of 120 proposals submitted to the program in 1995, the CEP was one of five that were funded. Bringing together experts in geology, seismology, geophysics, and geotechnical engineering, the CEP in 1996



Graph of compressional- (P) and shear- (S) wave velocities at the University of California at Riverside. The water table is indicated by the velocity increase in the P wave without an increase in S wave at the 71-meter depth, and the hard granite can be "seen" starting at 88-meter depth.



Schematic of the University of California at San Diego seismic station and data-handling system.

began a four-year examination of three specific sites: the Engineering 1 Building at Santa Barbara, the Thornton Hospital at San Diego, and the Rivera Library at Riverside.

Listening to the Underground

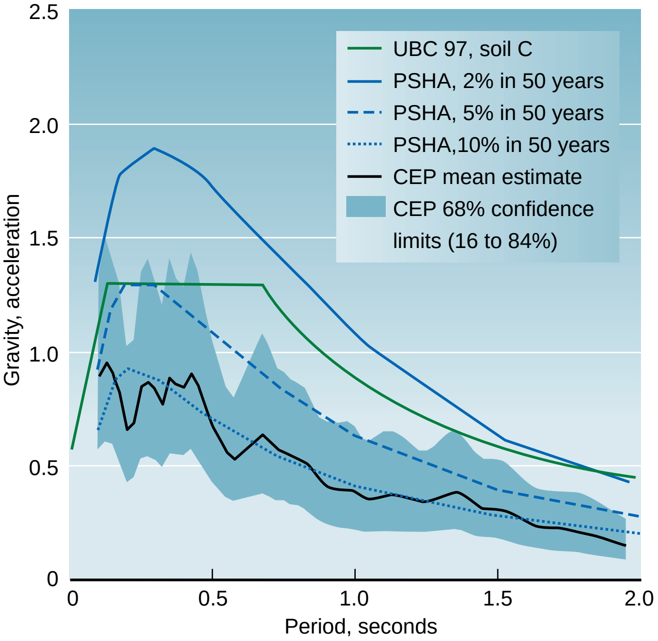
Given a site's ground motion—that is, how the site's geology responds to earthquakes—a structural engineer can design a building to withstand that motion. However, estimating the range of possible ground motions at a particular site requires a detailed knowledge of the site geology, the regional earthquake faults, and the site's response to seismic waves.

A geotechnical engineer draws on a variety of methods to determine what level of ground shaking should be considered in designing a structure to withstand earthquakes. One method, deterministic hazard estimation, focuses on designing a structure that could survive the largest earthquake expected at that site. Before this method is applied, the source (fault) and size (magnitude) of the threat must be determined. Another method, Probabilistic Seismic Hazard Estimation (PSHA), combines a variety of uncertainties—such as the likelihood of an earthquake of a certain magnitude occurring on a given fault—to estimate the probability of the structure experiencing a certain level of ground motion (or greater) during a specified time period.

The CEP provides site-specific seismic analyses by characterizing the geology of a given site, monitoring small local earthquakes at depth and on the surface, and using this information to model the strong motions of large earthquakes. The first step is to identify faults that could produce moderate to strong ground motion (defined as earthquakes of magnitude 6 and above on the Richter scale). The next step—characterizing the site—involves working out the details of the geology and the stratigraphy (the succession of geologic layers or strata). This work consists of drilling and sampling boreholes, collecting geophysical soil logs, making geotechnical measurements on soil samples, and pulling it all together to paint a detailed picture of subsurface geology. "This kind of exhaustive site characterization is seldom performed," says Heuze. "It is expensive and goes well beyond common site investigations. However, that is the price we must pay to obtain the credible site-specific knowledge required for predicting strong earthquake effects."

On each campus, the researchers placed seismic stations in vertical arrays as deep as 90 meters, far beyond the 30 meters typical of most geophysical examinations. The stations recorded small earthquakes from the local faults as well as regional events. Large earthquake motions for a given site were simulated using these data in combination with rupture scenarios of the faults identified as the main threats. Heuze explains, "For our calculations, we divide the fault surface into many subzones, sum up the contributions from small events in each subpart, and thus obtain the strong motion in rock under the site. We then calculate how that earthquake propagates up to the surface through the different soil layers." Rock's response to earthquakes is linear and fairly straightforward. But soils respond nonlinearly.

What can't be predicted is how an earthquake will break on a fault. It could fracture at one end and travel the length in one direction, or start at the opposite end. It could begin anywhere along the fault surface and travel in both directions, splitting the energy. Typically, the CEP analyzes over 100 rupture scenarios for each fault for a given earthquake magnitude. At the UC Santa Barbara site, for example, the team used 240 scenarios. The results of these estimates are then presented in terms of a stochastic distribution of possible motions for the campus.



Graph of surface strong-motion estimates for the University of California at Santa Barbara's Engineering 1 Building. The estimates are for the Uniform Building Code (UBC) 97 (green line), the Probabilistic Seismic Hazard Analysis (PSHA) with different earthquake likelihoods in a 50-year period (blue lines), and the Campus Earthquake Program (CEP) approach (the teal area defines the range for the mean ±1 standard deviation of the estimated earthquake motions).

"It is important to understand the difference between our approach, which is stochastic but deterministic, and the PSHA, which is strictly probabilistic," says Heuze. "We are not putting probabilities on our motions. We say that, whether the likelihood is low or high, they can happen, because nobody knows how the fault will rupture."

Rock-Bottom Line

Study results will be presented in a series of Lawrence Livermore reports, prepared with the campuses and available to the general public. In the reports, the site-specific ground motions calculated by CEP are compared to results obtained by other methods.

Heuze says, "Eventually, the University's decision on which motions to use as the design basis will depend on the combination of all the information it acquires. We are working closely with UC's consultants to combine the deterministic and probabilistic assessments, while also accommodating the regulatory constraints of building codes."

The CEP also has a proposal to perform a similar assessment for the site of the future UC Merced. Merced is the ideal study site, Heuze notes, because its ground-motion information would be available to the architects and structural engineers before they design any campus buildings.

Heuze adds, "This program is unusual in drawing, for the first time, upon the brain power within the UC system—professors, postdocs, and students at the campuses, scientists and engineers at Lawrence Livermore—to address the ground-motion problem facing the University. I see earthquake exposure to be the single greatest threat to the welfare of the University. Now, through this multidisciplinary effort, we can understand much more clearly the earthquake exposure that each campus faces."

—Ann Parker

Key Words: Campus Earthquake Program (CEP), Campus–Laboratory Collaboration Program, ground-motion analysis, Probabilistic Seismic Hazard Analysis (PSHA).

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