A Shaker Exercise for the Bay Bridge

CALIFORNIANS know this about earthquakes: they are bound to happen. Everyone knows that any number of seismic faults could produce The Big One, and most experts predict a large earthquake will occur in the San Francisco Bay Area within the next 30 years. We would like to be assured that construction codes for seismic safety are adequate and that buildings, roads, bridges, and other structures can stand up to any future earthquake. Unfortunately, that's just not so.

Confidence in public safety will grow if a group of scientists from Lawrence Livermore and the University of California (UC) at Berkeley has anything to do about it. Working in a campus–laboratory collaboration, they have been performing cross-disciplinary studies on earthquake hazards and are now performing computer simulations of the San Francisco Bay Bridge to find out how the bridge would respond to an earthquake along the nearby Hayward fault.

A site-specific analysis is requisite to confidence in predicting an earthquake's behavior and how a structure will respond to it. The Bay Bridge–Hayward fault project is the first step toward fuller delineations of earthquake risk so appropriate seismic safety measures for public structures can be implemented.

This particular simulation is also of interest because the Bay Bridge is a crucial transportation link in northern California. It carries the highest daily volume of traffic of any bridge in the U.S., and its long spans embody many seismic concerns. One span came undone in the 1989 Loma Prieta earthquake, prompting an overall seismic retrofit, soon to begin. In addition, the Hayward fault, located in a densely populated area and having a 50% probability of rupturing in a 30-year time frame, is considered the most dangerous of Bay Area faults. Seismologists think it could cause death and destruction comparable to that of the 1995 earthquake in Kobe, Japan, which resulted in 6,000 fatalities and over $100 billion in damage. The Bay Bridge is particularly vulnerable to the Hayward fault, located a mere 14 kilometers away.

The simulation is large and complex, requiring advanced numerical techniques, gigantic amounts of computational power, and the coupling of earth sciences and engineering know-how. Researchers can look forward to more massive computational power from the DOE Accelerated Strategic Computing Initiative's computers, which are used primarily to support stockpile stewardship and will enable even larger simulations.

Simulating the Earthquake

Before the bridge's response can be simulated, the rupturing of an earthquake fault must be simulated to generate ground motion information. A rupture of the Hayward fault was simulated with the powerful E3D seismic code developed by Livermore computer scientist and geophysicist Shawn Larsen. The code incorporates three-dimensional (3D) information about propagation of seismic waves: how they are radiated from the earthquake's source to the surface, at what velocities they propagate, and how they interact with the geology and topography in their path. Because the simulation involves distances to several hundred kilometers and depths to 50 kilometers, accurately predicting the strength and geographic distribution of seismic waves demands robust computing.

E3D integrates seismic information through a complex 3D geologic model of the San Francisco Bay Area, which was developed at UC Berkeley by Professor Doug Dreger and graduate student Christiane Stidham with funding from the U.S. Geological Survey. The model contains representations of large sedimentary basins (such as the San Pablo Basin, Santa Clara Valley, and Livermore Valley), deep crustal and mantle structures, near-surface alluvium and very low-velocity bay mud, high-velocity zones (such as Mt. Diablo), and seismic velocity contrasts across major faults in the region.

E3D has many advanced computational enhancements that allow it to run approximately a hundred times faster than other computational codes. In addition, it has been implemented on a variety of high-performance computers, including massively parallel processors.

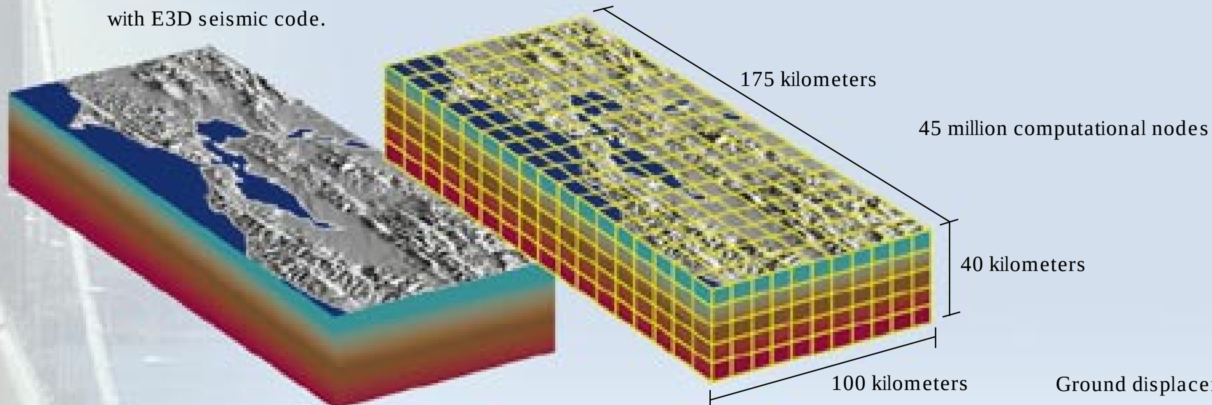
E3D's simulations of the Hayward fault represent the largest seismic simulation done anywhere in the world, with 45 million nodes of calculations. These three-dimensional calculations model the response of an entire seismogenic zone at the resolution needed to assess ground motion effects and the resulting earthquake hazards (see figure below).

The Bay Bridge in an Earthquake

The ground motion predictions from E3D are fed into SUSPNDRS, the code for simulating long-span bridge dynamics. A bridge's numerous interacting parts and connections can act and react differently to each other, resulting in structural changes and effects that are out of proportion to their causes.

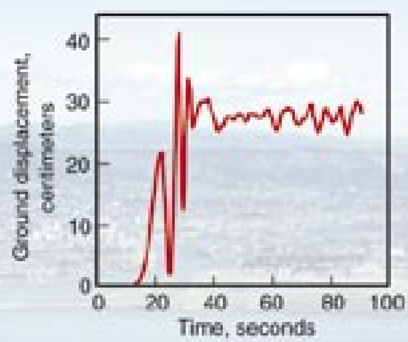
SUSPNDRS, a finite-element code developed by Livermore's David McCallen and UC Berkeley's Abolhassan Astaneh-Asl, incorporates algorithms that accommodate the nonlinearities in bridge geometry and material properties. The code also uses an efficient bridge model that represents the bridge structure through five components (towers, deck system, cable system, deck impacts, and piers) with reduced

San Francisco Bay Area modeled with E3D seismic code.

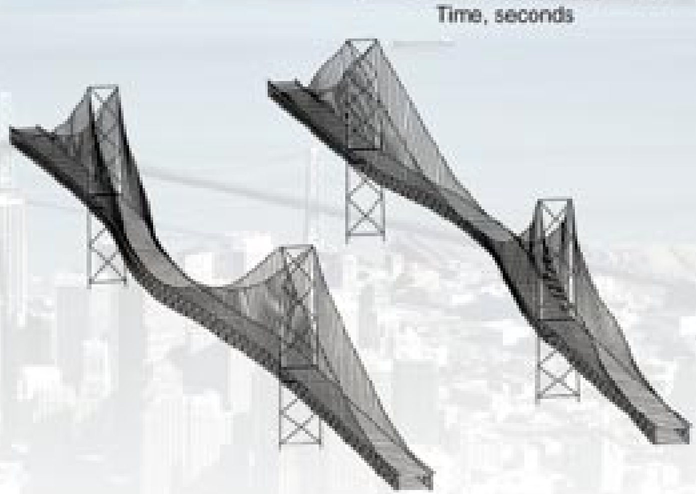


E3D simulations of an earthquake on the Hayward fault.

Ground displacement under the Bay Bridge from an earthquake on the Hayward fault.



SUSPNDRS code simulation of the Bay Bridge's dynamics.



degrees of freedom to save computational time without sacrificing essential bridge dynamics. SUSPNDRS efficiently performs calculations in three dimensions in a matter of three to four hours instead of the days or weeks required for such calculations in the past.

One unique feature of SUSPNDRS is the way its calculations are sequenced. By having the code emulate the construction sequence of the bridge components, McCallen and Astaneh-Asl could make the model calculations match actual forces and loads in key elements of the structure. They referred to construction drawings and historical construction documents to make their code calculations approximate the order of construction: towers erected, cables spun into place, stiffening trusses for the deck lifted segmentally into place, deck steel added, and finally the deck joints rigidly connected. The specific construction sequence has a significant effect on the final bridge deck member forces, so the computational model must reflect the same physical forces.

The figure on p. 19 also shows the bridge model where responses were simulated. The simulation results are now being validated. One validation method compares SUSPNDRS results with the first ambient measurements of bridge vibrations, collected in the 1930s with a vibrometer and documented in the *Bulletin of the Seismological Society of America*.

As bridge simulations progress, the work will focus on three seismic safety issues specific to long-span bridges: (1) the effect of a series of seismic waves on the bridge structure if, instead of propagating singly, they combine into one large-amplitude wave; (2) the effects caused by waves arriving at different times at different points of a structure; and (3) permanent ground deformations occurring near the ruptured fault that would affect the nearby bridge structure. Because few measurements exist of this important near-field phenomenon, large-scale simulations are providing new understanding for seismologists and engineers.

The long-term results of this campus–laboratory collaboration will enhance seismic safety in California. In the interim, the Bay Bridge results may benefit retrofit efforts for one of the Bay Area's most important long-span bridges.

— Gloria Wilt

Key Words: bridge dynamic analysis, campus–laboratory collaboration, E3D, earthquake simulation, earthquake risk assessment, Hayward fault, hazard assessment, San Francisco Bay Bridge, seismic safety, SUSPNDRS.

For further information contact Shawn Larsen (925) 423-9617 (larsen8@llnl.gov) or David McCallen (925) 423-1219 (mccallen2@llnl.gov).
Internet address: www-ep.es.llnl.gov/www-ep/ghp/Larsen/Hayward/hayward.html

Forensic Science Sleuthing

Figure 1. When the Army unearthed more than a thousand mortar rounds dating from a World War II training area, they enlisted the Laboratory's Forensic Science Center to determine which were live munitions and which were dummies.

LIKE high-tech colleagues of Sherlock Holmes, experts from Lawrence Livermore's Forensic Science Center develop sophisticated analytical equipment for combatting terrorism and the proliferation of weapons of mass destruction, supporting stockpile stewardship efforts, and responding to law-enforcement requests. Using center-developed prototypes, these experts in organic, inorganic, biological, and nuclear chemistry can determine the composition and often the source of the most minute samples of evidence. The sophistication of their sleuthing is beyond the wildest dreams of even Mr. Holmes and Dr. Watson.

Past issues of this publication have detailed the techniques of the center (*E&TR*, March 1994, pp. 1–8; and *S&TR*, August 1995, pp. 24–26). Some of the systems and methods have now "come of age" and are used in the field for remote analyses and real-time results.

This summer in Cape Cod, Massachusetts, the center first used its portable thin-layer chromatography system in the field for the first time. This system interrogated the interior of more than a thousand munitions dating back to World War II. The center also placed modern solid-phase microextraction (SPME) sampling tools at a Department of Energy weapons plant to monitor the safety and efficacy of the current nuclear stockpile. In the law-enforcement arena, the center is a key participant in the new partnership between the Federal Bureau of Investigation (FBI) and Lawrence Livermore (see the box on p. 22).

Blast from the Past

During an environmental cleanup operation at the Massachusetts Military Reservation in the spring of 1998, Army personnel discovered a suspicious depression in an area once used for training. The depression turned out to be the "burial ground" for mortars and ordnance that had been used during target practice exercises (Figure 1). Three questions needed answers: How many of the munitions were "live"? How should they be rendered safe? What was the best way to dispose of them?

Brian Andresen, director of the Laboratory's Forensic Science Center, assessed the situation at the request of the Defense Ammunition Center. His initial samples indicated that approximately one munition out of ten was live, while the rest were dummies of wax and plaster of paris. Although they couldn't explode, the dummies did have live fuses, and some of the rounds—the exact quantity unknown at that point—could have contained appreciable quantities of high explosive (HE).

Andresen recommended cutting each of the thousand-plus mortars in half and sampling them for HE. The Army agreed, so in July 1998 Livermore's Jeff Haas and Greg Klunder packed up sampling kits and analysis equipment and headed east.

The project was an ideal test case for the center's thin-layer chromatography (TLC) screening system, which was originally developed as a field-portable propellant analysis system for the Department of Defense. Propellants (essentially HE) require stabilizers (such as diphenylamine) to prevent spontaneous ignition. Because stabilizers are depleted by extended exposures to high temperatures, the military needed a way to quickly determine the safety of large numbers of bulk propellants. The TLC system screened the Army site for explosive compounds. Sensitive and fast, the system required only 50-milligram samples of explosive, instead of the gram quantities required by other methods, and 15 minutes for each group of 20 samples.

Haas and Klunder analyzed 1,236 mortar rounds in two days (Figure 2). With the real and dummy munitions identified, the Army sent the dummy pieces to a military salvage yard and safely disposed of the remaining live shells. In the past, normal protocol was to group the mortars—live ones and dummies together—in piles of 100 and to explode them all, but that solution is no longer considered environmentally acceptable.

The nearby town of Borne also gained peace of mind from the center's analysis. The work demonstrated that the HE amounts were insignificant and that environmental contamination did not occur while the munitions were buried.

Back to the Future for the Stockpile

In 1998, center staff also developed methods for verifying the safety of the weapons systems in the U.S. nuclear stockpile.

"Our task was to provide a way of determining the condition of a nuclear weapon's internal components without using either electricity or light and without disturbing the weapon's internal geometry," said Andresen.

The materials in a modern nuclear weapon include highly sensitive and reactive components, such as plutonium and uranium, as well as organic materials. These organic materials include the HE that initiates the nuclear fission reaction as well as structural materials and adhesives that maintain precise internal alignments. Such materials are stable polymers with small diffusion coefficients (10^{-11} to 10^{-5} square centimeters per second). However, in the weapon environment—over a period of many years, at elevated temperatures, in a hermetically sealed radioactive environment—certain systems may outgas at detectable levels. When outgassing, these organic materials release compounds that can indicate problems such as corroded metals, degrade components that affect the overall integrity of other warhead materials, and generally signal decomposition of materials within the warhead. By monitoring these chemicals, experts are alerted to problems that may be developing inside the weapon.

Figure 2. Livermore's Jeff Haas sampled over 1,200 mortars in two days using the center's unique thin-layer chromatography screening system.

Recipe for Safety: Yellow Cake and Simple Green

In the summer of 1998, Secretary of Energy Bill Richardson announced a new partnership between the Federal Bureau of Investigation (FBI) and Lawrence Livermore to combat international terrorism with high technology. This formal partnership affirms the role the Forensic Science Center plays in supporting forensic investigations.

Two recent incidents—both with happy endings—demonstrate the speed and efficiency with which the center responds to urgent requests from law-enforcement agencies and nuclear regulators.

The first incident involved unknown material in a coffee can obtained by a high school student at a local swap meet. The material—a light yellow, very fine powder—was confiscated by the school. The material was discovered to be radioactive, and the center was called in by DOE.

Nuclear chemist Ken Moody performed the analysis and relayed the results back to DOE within 16 hours of receiving the material. "Since everyone was anxious to get immediate results, we expedited nuclear counting techniques and assayed the material with gamma-ray spectrometry and alpha-particle spectroscopy. We measured no radionuclides above background other than unperturbed isotopes of uranium. The material was naturally occurring uranium, or yellow cake, not an enriched or otherwise processed uranium compound."

The second incident occurred as FBI agents searched the Los Angeles home of a man arrested for stealing military weapons. Among an arsenal of assault rifles, hand guns, explosives, and heavy-duty flak vests, they found a jar of green liquid labeled "poison." Concerned that the liquid might be a chemical warfare agent, the FBI contacted the center.

"Rich Whipple and I conducted field sampling within an FBI-controlled area," explained Pat Grant, deputy director of the center. "We put the sample—which had been well packaged by a hazardous materials team—into a containment glovebag inside a field-portable hood. Using the solid-phase microextraction (SPME) technique, we exposed two microfibers, one at a time, to the liquid and then repackaged the jar. We transported the SPME fibers to the center in O-ring-sealed metal containers. Armando Alcaraz performed gas chromatography–mass spectrometry (GC–MS) analyses, we analyzed and interpreted the data, and the results were reported to the FBI just two-and-a-half hours after the start of our investigation."

Good news. The green substance turned out to be a nontoxic cleaning solution. In fact, the next day Whipple brought in a commercial "simple green" household cleanser and ran a SPME GC–MS analysis of the fluid. The chemical signatures of the commercial product and the suspect solution were virtually identical.

The techniques and analytic protocols rely on center-developed solid-phase microextraction (SPME), which allows rapid and efficient environmental sampling and processing. The key to microextraction is a minuscule fiber inside a syringe needle (Figure 3). The fiber is coated with an adsorbant that, when exposed to the ambient environment, collects the molecules of a suitable sample.

Five types of fiber with specialty polymer coatings are available commercially. For example, one fiber picks up acids in preference to bases; another extracts alcohol more efficiently than hydrocarbons. Each SPME fiber coating can collect thousands of different compounds of a specific class after only a few seconds of sampling time. Before the development of this technique, it took weeks to collect and characterize only a few tens of unknown compounds from warhead materials.

In the SPME project, chemists David Chambers and Heather King are identifying the gas-phase chemicals in a weapon's primary headspace and studying their time histories. "In the first phase of this project, we're identifying what chemicals, if any, are emitted by weapon components," said Chambers, the project's principal investigator. "So far, we've characterized weapons-material components as well as HE associated with two weapons systems."

The most recent stockpile stewardship application of the SPME technique involves monitoring the headspace of individual warheads. For instance, at the Pantex Plant in Amarillo, Texas, SPME is being used with other types of nondestructive surveillance to monitor 10 weapons.

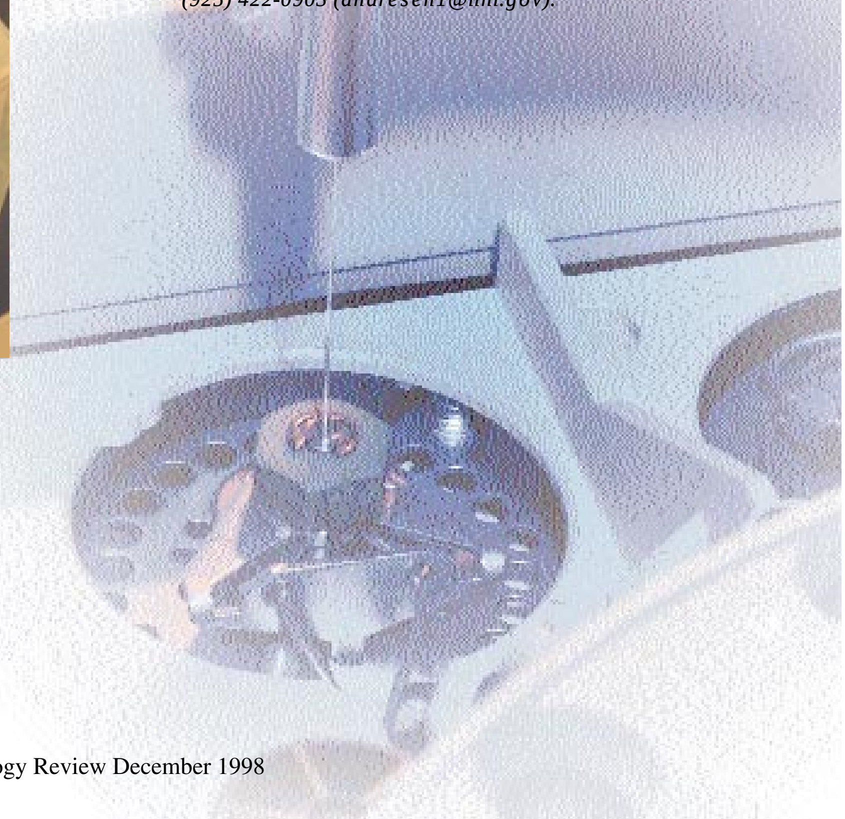


Figure 3. (above) Heather King and David Chambers demonstrate Livermore's solid-phase microextraction (SPME) sampling technique. The microfiber inside the syringe is coated with a special polymer that collects molecules of gas-phase chemicals. (right) The fiber is then desorbed in the injection port of a gas chromatograph–mass spectrometer, which identifies the compounds and measures their amounts.

The Future of Forensic Analysis

The term "forensic science" used to apply only to the scientific analysis of evidence in the context of civil or criminal law. Increasingly, forensic analyses are used to monitor or verify compliance with international treaties and agreements—particularly those involving weapons of mass destruction—and for stockpile stewardship.

A busy future of forensic science was recently underscored by DOE Secretary Bill Richardson in his August 1998 visit to Lawrence Livermore, when he announced that the Laboratory was the first in a "network of premier laboratories around the country that will give the FBI next-generation crime-fighting capacity."

Holmes and Watson would be proud!

— Ann Parker

Key Words: Federal Bureau of Investigation (FBI), Forensic Science Center, gas chromatograph–mass spectrometer (GC–MS), solid-phase microextraction (SPME), thin-layer chromatography (TLC).

For further information contact Brian Andresen (925) 422-0903 (andresen1@llnl.gov).