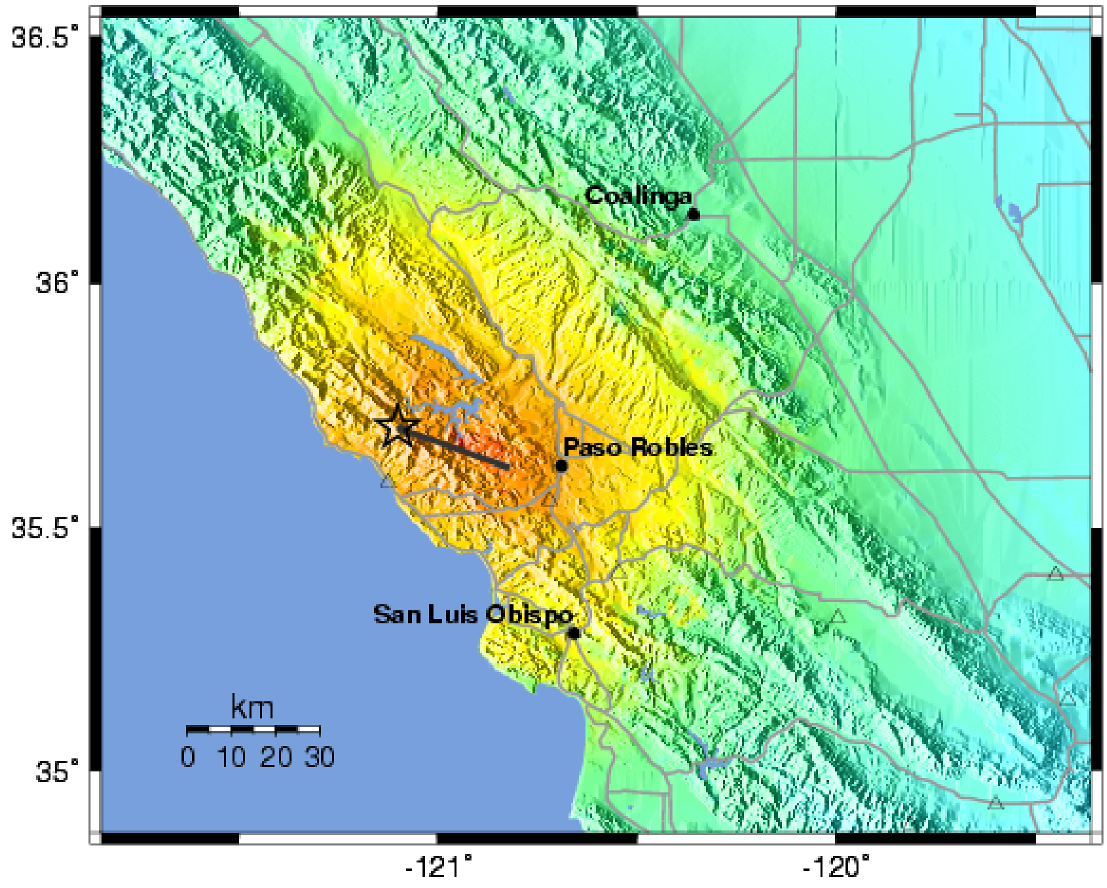
Performance of the CISN during the 2003 San Simeon Earthquake



California Integrated Seismic Network

CISN California Integrated Seismic Network
California's Partner to the ANSS Advanced National Seismic System

CGS USGS OES Caltech UC Berkeley

Executive Summary

The San Simeon earthquake provided the first significant test of California Integrated Seismic Network (CISN) capabilities since the initiation of the statewide collaboration. The event highlighted some known issues and illuminated some new areas for focus. In this report, we document how the CISN organization responded to the quake. Overall, the CISN performance for the distribution of information following the San Simeon earthquake was good. Automatic information about the location was available within 30 seconds and a final location with a reliable magnitude was released about 4.5 minutes after the event. The first ShakeMap was issued 8 minutes after origin time and distributed to OES and multiple Web servers. During the next 24 hours, additional information about aftershock probabilities, the fault rupture, and seismological/engineering aspects of interest were made available by the CISN. However, one of the most challenging aspects of this event was the lack of digital stations in the vicinity of the earthquake. This compromised the quality of the ShakeMaps for the mainshock and aftershocks, as well as posing limitations in our ability to obtain reliable locations and magnitudes for the smaller events. Although the greater Los Angeles area and the San Francisco Bay region are approaching sufficient station density to provide data-driven ShakeMaps, significant portions of California lack the necessary coverage.

Introduction

The CISN is a collaboration among federal, state, and academic institutions engaged in earthquake monitoring in California and represents California as a designated region of the Advanced National Seismic System (ANSS). With support from the ANSS program of the United States Geological Survey (USGS) and the California Office of Emergency Services, the CISN partners (USGS, California Geological Survey, UC Berkeley, and Caltech) are engaged in an effort to improve seismic monitoring in California.

The December 22, 2003 M6.5 San Simeon earthquake is the largest event in California since the 1999 M7.1 Hector Mine earthquake. The earthquake provides the opportunity to review the progress of the CISN toward its goals, which are to:

- Operate a reliable and robust statewide system to record earthquake ground motions over the relevant range of frequencies and shaking levels
- Distribute information about earthquakes rapidly after their occurrence for emergency response and public information
- Create an easily accessible archive of California earthquake data for engineering and seismological research, including waveform data and derived products
- Maintain CISN infrastructure as a reliable state-of-the-art data collection, processing, and information distribution system
- Apply the latest research and technology to develop new algorithms for analyzing earthquake data and extracting more detailed information for new user products
- Maximize the use and benefit of real-time seismic information and other rapidly evolving tools and technologies through technology transfer to the user community

This report provides an overview of the San Simeon earthquake, in terms of the preliminary science and engineering results, but focuses primarily on the operation and response of the CISN. Some of the text is taken from the CISN preliminary online report on the San Simeon earthquake (Hardebeck et al., 2004).

Overview

A magnitude 6.5 earthquake struck the central California coast on December 22, 2003 at 11:15:56 AM (PST), 11 km NE of San Simeon and 39 km WNW of Paso Robles (Figure 1). Two deaths occurred due to the collapse of the Acorn building in Paso Robles and approximately 50 people were injured. Preliminary reports suggest that the most severe damage was to unreinforced masonry structures that had not yet been retrofitted (e.g., EERI, 2004). Significant damage to water tanks has also been reported and a number of wineries suffered significant loss of wine barrels and their contents.

Numerous active faults are mapped (Jennings, 1994) in the epicentral region (Figure 1), but it is not yet clear which, if any, of these mapped faults may have ruptured during the quake. No surface rupture from the earthquake has been identified. Road buckling and reported surface breaks all appear to be secondary deformation due to earthquake shaking, not surface rupture of the main fault. Many landslides and liquefaction features have been found, typical for an earthquake of this size.

The San Simeon earthquake was a reverse event, where one side of the fault overrides the other side on an inclined fault plane. Such reverse earthquakes are not uncommon in central California (McLaren and Savage, 2001) and are caused by a small compressional component of the motion between the North American and Pacific plates. Other reverse earthquakes of nearly the same size in central California include the 1983 Coalinga (M6.4) and the 1985 Kettleman Hills (M5.9) earthquakes. Analysis of events north of the epicentral area also show reverse mechanisms, although the 1952 M6.2 Bryson earthquake has a strike-slip first-motion mechanism (Dehlinger and Bolt, 1987).

The relatively shallow event (the hypocenter was located at a depth of 8 km) uplifted the Santa Lucia mountains and triggered a vigorous aftershock sequence. Approximately 3000 aftershocks above M1.5 and 230 above M3 were recorded in the first month since the temblor, and they are expected to continue for several years. The aftershocks extend southeast from the epicenter, in a zone approximately 35 km long (Figure 2).

Damage reports and personal experiences during the mainshock continue to be compiled. For example, the USGS Community Internet Intensity Map (CIIM, also known as "Did You Feel It") (Wald et al., 1999b) has received nearly 17,000 reports as of mid-March, 2004. Although this area was not densely instrumented (see below), an acceleration recording of 47%g was observed at the first floor of Templeton Hospital. The Templeton Hospital is off the southeast end of the rupture and may be representative of the highest ground motions in this earthquake because the rupture propagated from the hypocenter toward the southeast.

As demonstrated in damage reports, directivity contributed significantly to the strong shaking experienced during the San Simeon earthquake. However, the directivity focusing was minimized in this event because the slip direction was perpendicular to the rupture direction. The same slip distribution on a vertical strike-slip fault (similar to the 1952 Bryson earthquake) would have produced ground motions 2-3 times higher in some areas.

As a side note to the event, numerous people in the Cambria area have reported "shaking" or "rumbling" around 10:40 AM on Dec 22, prior to the M6.5. Analysis of data from a nearby NCSN site shows ground motion typically associated with sonic booms and not earthquakes.

Earthquake system performance

The CISN is organized so that routine earthquake processing is the responsibility of Northern and Southern California Management Centers. The San Simeon earthquake occurred in central California, within the region of responsibility of the USGS Menlo Park and UC Berkeley Northern California Management Center (NCMC).

The automated procedures of earthquake location and magnitude determination worked well (Tables 1 and 2). A preliminary location was available within 30 seconds, and a final location with a saturated duration magnitude (M_d) of 5.6 was released approximately 4 minutes after the event occurred. An updated and more reliable local magnitude (M_L) of 6.4 was released 30 seconds later, and the final moment magnitude (M_w) of 6.5 was released 6.5 minutes after the earthquake origin time.

The automatically determined first motion mechanism and moment tensor solution each showed a reverse mechanism, in excellent agreement with the reviewed mechanisms.

To meet the goal of operating a robust and reliable system, the CISN partners have been working to establish a statewide monitoring system. For the previous six months, the partners had been working on a trial configuration that combines the northern and southern California phase arrival time information. This prototype system for the detection and location of earthquakes statewide was running in a test mode and performed well for the San Simeon sequence. Additional work is underway to complete the determination of magnitudes statewide.

In parallel, the CISN partners have been working together toward a common software system. The NCMC is currently working on a new processing system and is working with the Southern California Management Center (SCMC) (USGS Pasadena and Caltech) to build on the software framework developed under the TriNet project. Developers at the Northern and Southern California Management Centers have been sharing software and coordinating development efforts with the goal of migrating toward a unified system. This effort goes beyond the original CISN plans for calibrating software which did not require the same codes to run at both the NCMC and SCMC. This new direction has both short-term and long-term benfits for the CISN - from bug fixes to shared maintenance and ongoing development.

ShakeMaps

ShakeMaps (Wald et al, 1999a) have emerged as an important tool for earthquake emergency response. Developed as part of the TriNet project, they portray the distribution of ground shaking. Enhancing the robustness of the computational infrastructure, increasing data availability, and improving the distribution of ShakeMaps has been a high priority for the CISN.

One of the most challenging aspects of this event was the lack of ShakeMap-quality stations in the vicinity of the earthquake, particularly stations with communications capability. *ShakeMap-quality stations* are sites with digital strong-motion accelerographs located in the free-field or in small buildings. The closest such station to the epicenter with continuous telemetry was the UC Berkeley station PKD, in Parkfield, CA, at a distance of 56 km. The California Geological Survey (CGS) operates three stations in the area - Cambria at 13 km, San Antonio

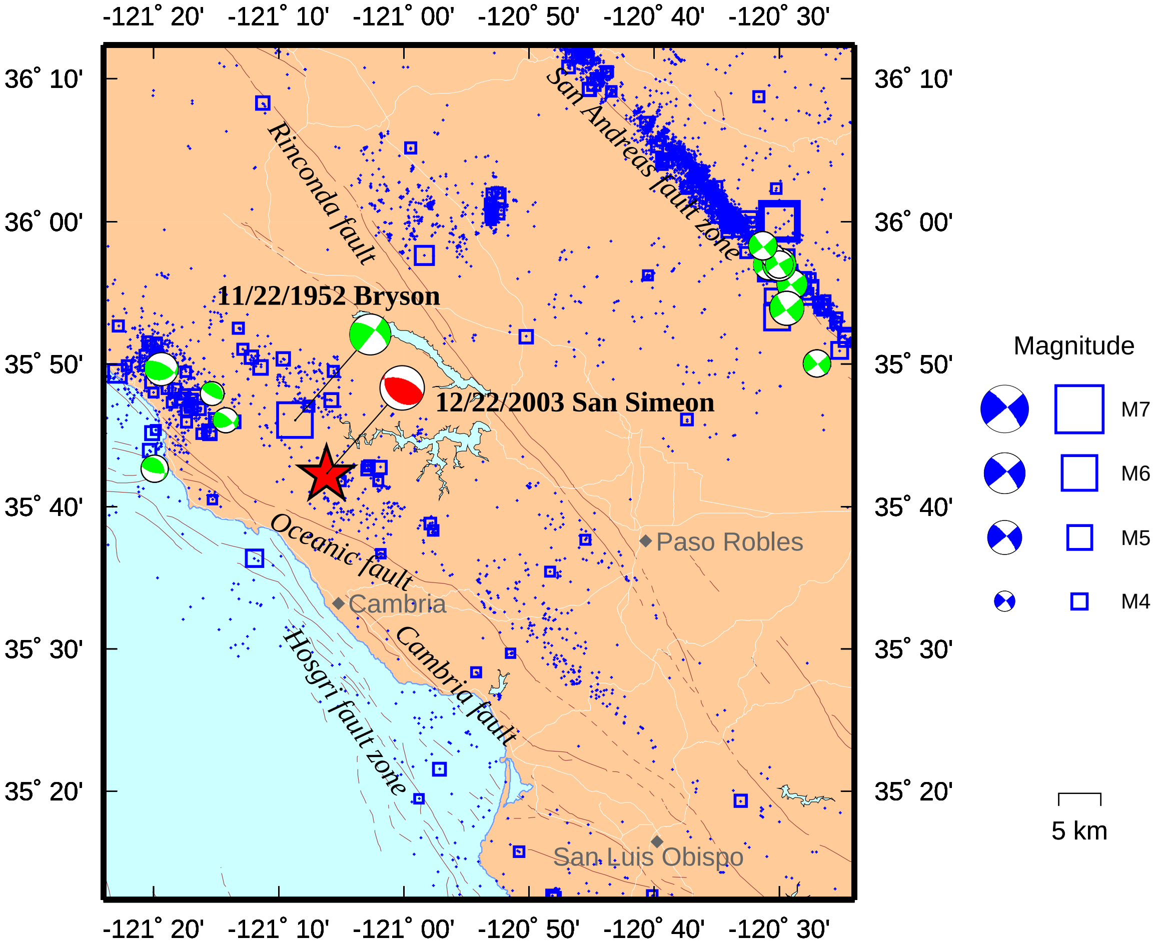


Figure 1: Map showing the background seismicity from 1966-2003 in the region of the San Simeon earthquake. Earthquakes with magnitude less than 3 are plotted as points; events with magnitude greater than 3 are plotted as squares. Moment tensors solutions over the last 10 years are plotted in green. The location and mechanism of the M6.5 are shown in red. Also shown is the location and first-motion mechanisms of the 1952 Bryson earthquake (Dehlinger and Bolt, 1987).

Dam at 22 km, and Templeton at 38 km from the epicenter. However, since these stations did not have telemetry, their data were not available until hours after the earthquake. Caltech/USGS Pasadena operate stations to the south of the event, but their nearest station was 60 km from the epicenter.

The first automatic ShakeMap was posted 8 minutes after the event, based on the M_L of 6.4 and with 29 stations contributing. The first update occurred 6 minutes later based on the revised M_w of 6.5 and the addition of 45 stations (mostly distant). Throughout December 22nd and 23rd, the ShakeMap was updated multiple times with additional data (including the observations from the CGS stations at Templeton and Cambria) and as more information about the earthquake rupture (fault orientation and length) became available.

The lack of nearby ShakeMap-quality stations resulted in maps with an overwhelming reliance on theoretically predicted ground motions. Figure 3 illustrates the evolution of the intensity map with time. In Figure 3a and b, the source is modeled as a point source and the maps show areas of significant ground motions south and north of the epicenter. Four hours after the earthquake, information about the fault rupture was added (c), based on the inversion results of Dreger et al. (2004, see below). The addition of the finite fault information (in this case, limited to the linear extent and orientation of the fault) focused the higher ground motions to the southeast and showed more damaging shaking in the vicinity of Paso Robles. However the most significant change in

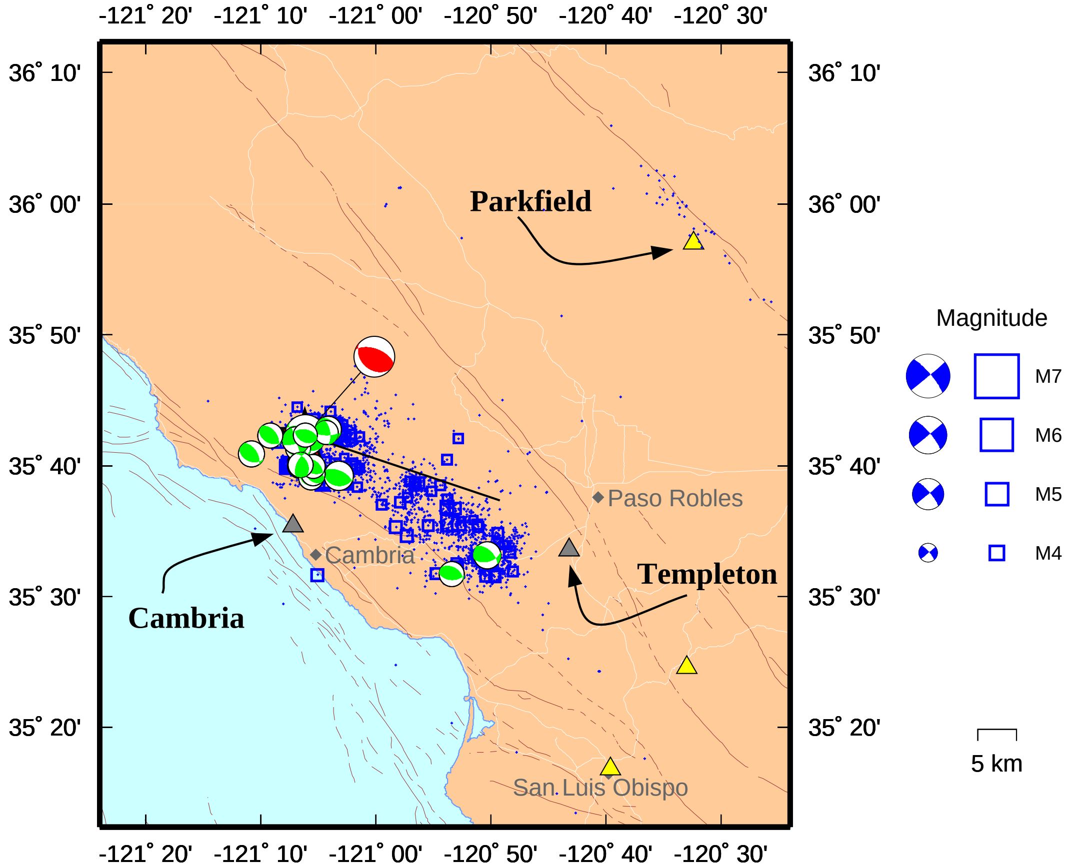


Figure 2: Earthquakes and moment tensors in the region of the San Simeon earthquake since the 12/22/03 mainshock. The aftershock region extends from the mainshock to the southeast. The solid line indicates the extent of the line source determined on the 22nd for improving the ShakeMap. Triangles indicate the location of stations used in the ShakeMap - yellow indicates near real time stations; grey indicates stations without communications that were not available in near real time. Stations mentioned in the text - Cambria, Templeton, and Parkfield - are labelled.

the ShakeMap came with the addition of data from the Templeton station, seven hours after the earthquake (d). The high shaking observed at Templeton (47% g), raised all the intensity levels significantly. Maps (e) and (f) show the intensity level after the addition of the Cambria data and the map as of January 5, 2004.

Only a few ShakeMaps have made use of finite source information in the past - the 1999 Hector Mine and 2001 Denali earthquakes are examples. Although the use of finite source information is not automated, the CISN is making progress toward the rapid determination of these parameters as described below. Because this component of the system has been seldom exercised, the San Simeon earthquake uncovered a problem in the code used to compute distances to a rupture segment. As a result, the ShakeMaps in Figure 3c-f under estimate ground motions near the middle of the fault trace. Figure 4 displays the revised intensity map, which shows a broader area of intensity VIII than observed in Figure 3f.

Comparison of Figure 4 with the USGS Community Internet Intensity Map (CIIM) (Wald et al., 1999b) shows generally good agreement in levels of intensity, although the CIIM indicates a higher level of earthquake effects south of San Luis Obispo than captured by the ShakeMap.

The paucity of ShakeMap-quality stations is readily apparent in all maps from Figure 3. The dependence of the ShakeMaps on the Templeton data illustrates the importance of having nearby ShakeMap-quality stations with telemetry so that the CISN can produce reliable information for post-earthquake applications such as emergency response and damage estimation.

CISN Timing		
Earthquake Information	UTC Time	Elasped time (HH:MM:SS)
Origin Time (OT)	12/22 19:15:56	00:00:00
Quick Look hypocenter	12/22 19:16:20	00:00:24
Final hypocenter & M_d	12/22 19:20:25	00:04:29
Local Magnitude	12/22 19:20:58	00:05:02
First Motion mechanism	12/22 19:21:36	00:05:40
Moment Tensor mechanism & M_w	12/22 19:22:40	00:06:44
1st ShakeMap completed (M_L 6.4)	12/22 19:24:13	00:08:17
Analyst review/1st aftershock probabilty	12/22 19:32:00	00:16:04
2nd ShakeMap completed (M_w 6.5)	12/22 19:38:28	00:22:32
Analyst review of moment tensor	12/22 20:16:49	01:00:53
1st Internet Quick Report at cisn-edc.org	12/22 20:30:–	01:14:–
Analyst review of line source	12/22 21:54:–	02:38:–
ShakeMap update with line source	12/22 23:33:–	04:17:–
ShakeMap update with Templeton data	12/23 02:34:–	07:18:–
Earthquake Report at cisn.org	12/23 17:34:–	22:18:–
Updated aftershock probabilty	12/23 22:54:–	27:38:–
ShakeMap update with Cambria data	12/24 00:28:–	29:12:–
Preliminary science report at cisn.org	12/24 23:44:–	52:28:–

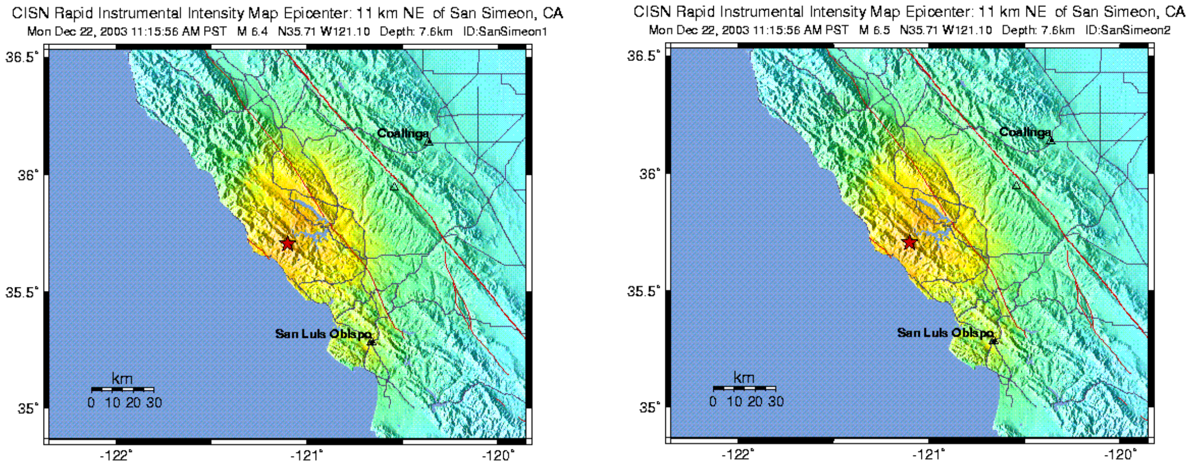
Table 1: Timing of earthquake information for the San Simeon earthquake.

Parameters of the Dec 22, 2003 San Simeon Earthquake		
	Automatic	Reviewed
Origin Time (UTC)	19:15:56.24	19:15:56.20
Location (latitude longitude)	35.7058 -121.1013	35.7043 -121.1032
Depth (km)	7.59	7.34
M_d	5.62	5.35
M_L	6.43	6.44
M_w	6.50	6.50
FM Mechanism (strike/dip/rake)	297/56/97 105/35/80	305/60/71 160/35/120
MT Mechanism (strike/dip/rake)	294/59/83 128/32/102	290/58/78 131/34/108
MT Depth (km)	8.0	8.0

Table 2: Comparison of parameters as determined by the automatic earthquake processing system with those obtained after analyst review. Note that the value of M_d is lower than the M_L or M_w as the duration magnitude estimate generally saturates around M4.0-4.5. FM - first motion; MT - moment tensor.

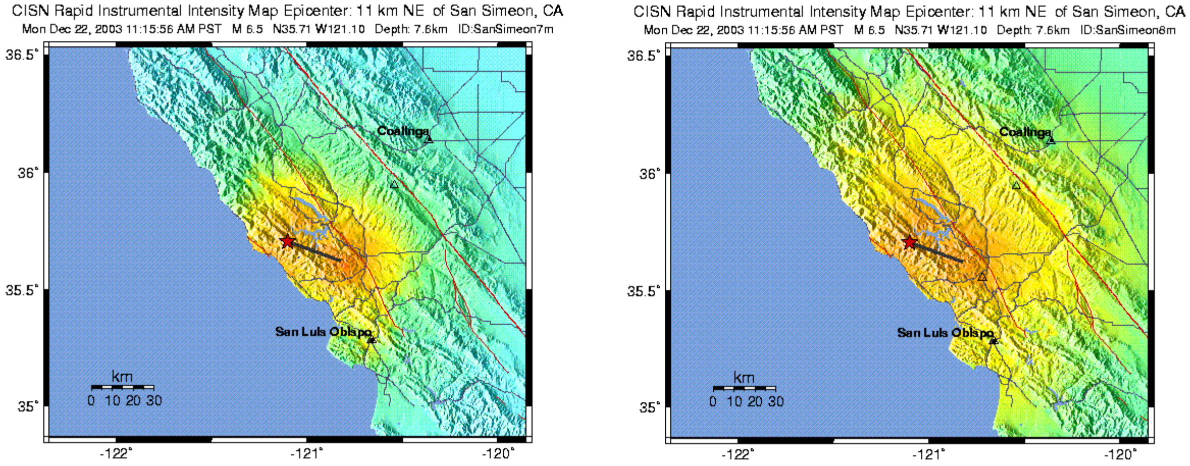
The experience of the San Simeon earthquake ShakeMap provided several lessons for the CISN. The location of this event near the boundary of the northern and southern California processing systems highlighted the importance of data exchange. In June of 2003, the CISN partners began implementing a system for exchanging strong-motion parameters, based on the Earthworm ground motion II format and a series of automated file transfer programs. As a result, ground motion data are distributed to all partners as they are processed, providing each processing center with a complete view of all data. As a result of this developmental system, the NCMC had rapid access to data from CGS, USGS Menlo Park, USGS NSMP, and UC Berkeley for ShakeMap generation. However, this system was not fully implemented at the time of earthquake, and a key component of the system stopped functioning on Dec 16th. Because this developmental software was not monitored, CISN staff were not automatically alerted to the problem and data from the closest SCMC stations were not available in real-time for the ShakeMap. The CISN partners completed the majority of this installation in February, 2004 and the system is now fully implemented with heartbeats and other components for the detection of state-of-health.

Another lesson from the San Simeon experience was related to scheduling of ShakeMap "updates." At the time



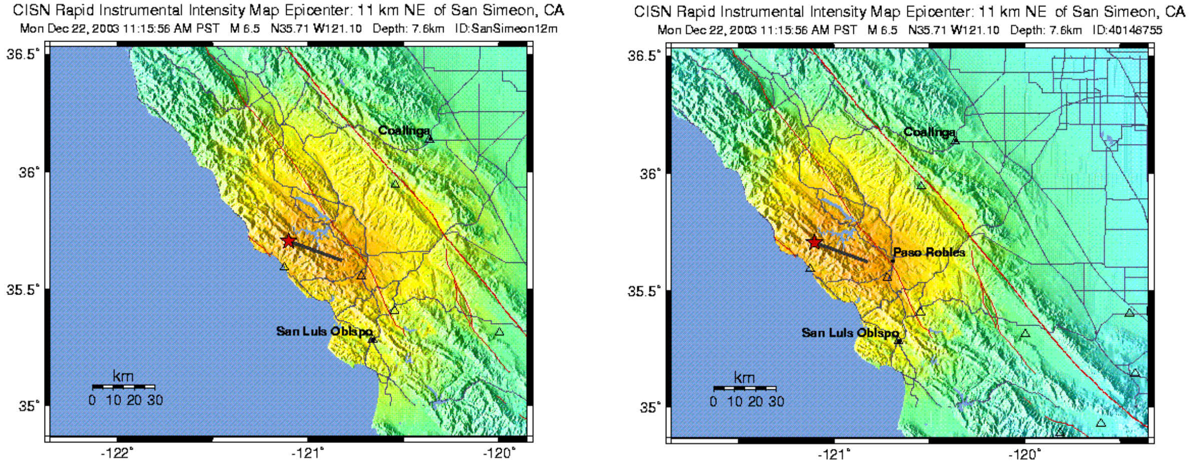
A: 12/22 11:24 AM First ShakeMap with ML 6.4.

B: 12/22 11:38 Update with additional stations and Mw 6.5



C:12/22 15:33 Update with addition of finite fault description.

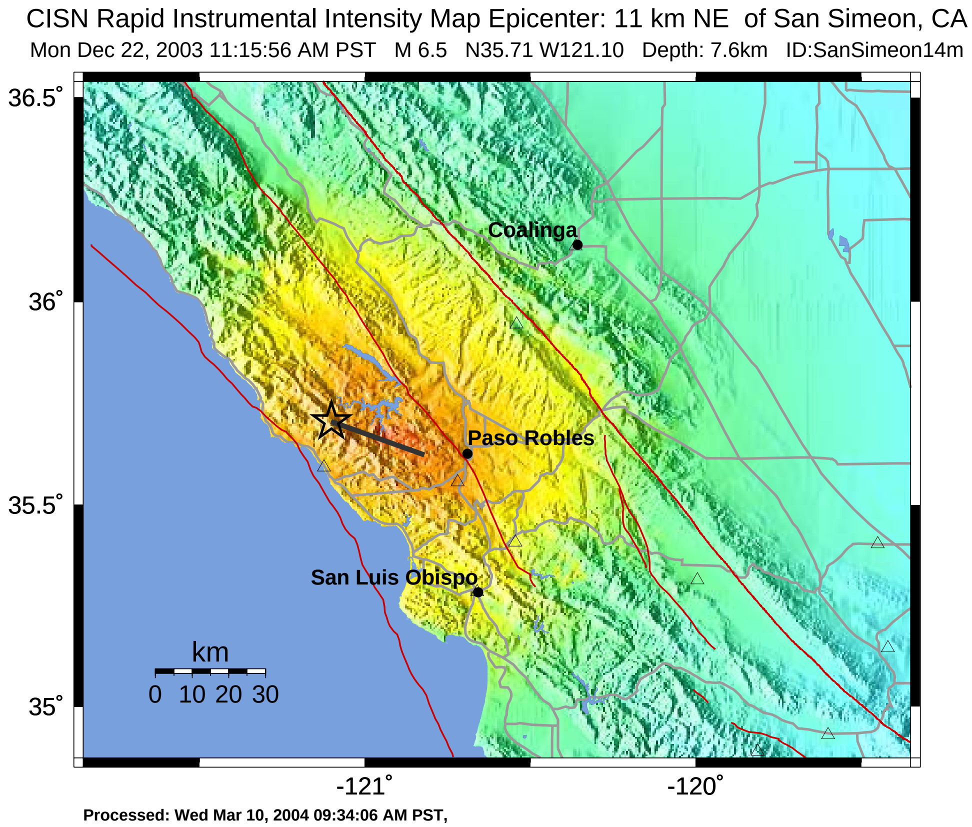
D: 12/22 18:34 Update with data from the Templeton station.



E: 12/23 16:28 Update with data from the Cambria station.

F: ShakeMap as of 1/5/2004.

Figure 3: The temporal evolution of ShakeMaps for the San Simeon earthquake, as illustrated through the intensity maps. All times are local.



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+**

Figure 4: Map of instrumental intensity for the M6.5 San Simeon earthquake, after correction for the fault distance calculation.

of the earthquake, the NCMC system was scheduled to automatically update at 5, 15, 30 and 60 minutes after the initial run. However, the mix of real-time and non-real-time stations in northern California means that data can trickle in over a period of several days. As a result of the San Simeon experience, the NCMC has restructured the ShakeMap scheduling so that the system will check for new data and/or a revised magnitude at 5, 15, 30 and 60 minutes after the first run, then every hour for the next six hours, followed by every six hours until 48 hours after the initial run. If new data are found, the ShakeMap will be updated. In the long term, we plan to implement a system similar to the one at the SCMC, where the ShakeMaps are rerun when new data arrive.

The San Simeon earthquake highlighted other issues related to ShakeMap, and the CISN has established a working group to examine these. For example, the working group is currently discussing methods to grade or assess the quality of a ShakeMap as well as to provide a spatial representation of the uncertainty of map. The CISN working group is collaborating with David Wald of the USGS to develop and test several ideas for quantifying ShakeMap. Ideas under discussion range from a simplistic approach where a grade could be based on concepts already in use for location quality such as the number of observations, the distance to the nearest station and the azimuthal distribution, and some measure of completeness of coverage as well as a more sophisticated effort to quantify the map at each grid point based on its proximity to an observation as well as to the earthquake rupture. This effort is underway, with the goal of having several metrics to test in the coming months.

The ShakeMap working group is also developing a design for computing and presenting uniform ShakeMaps statewide. The current focus is on developing a Web interface to provide unified access to ShakeMaps. The

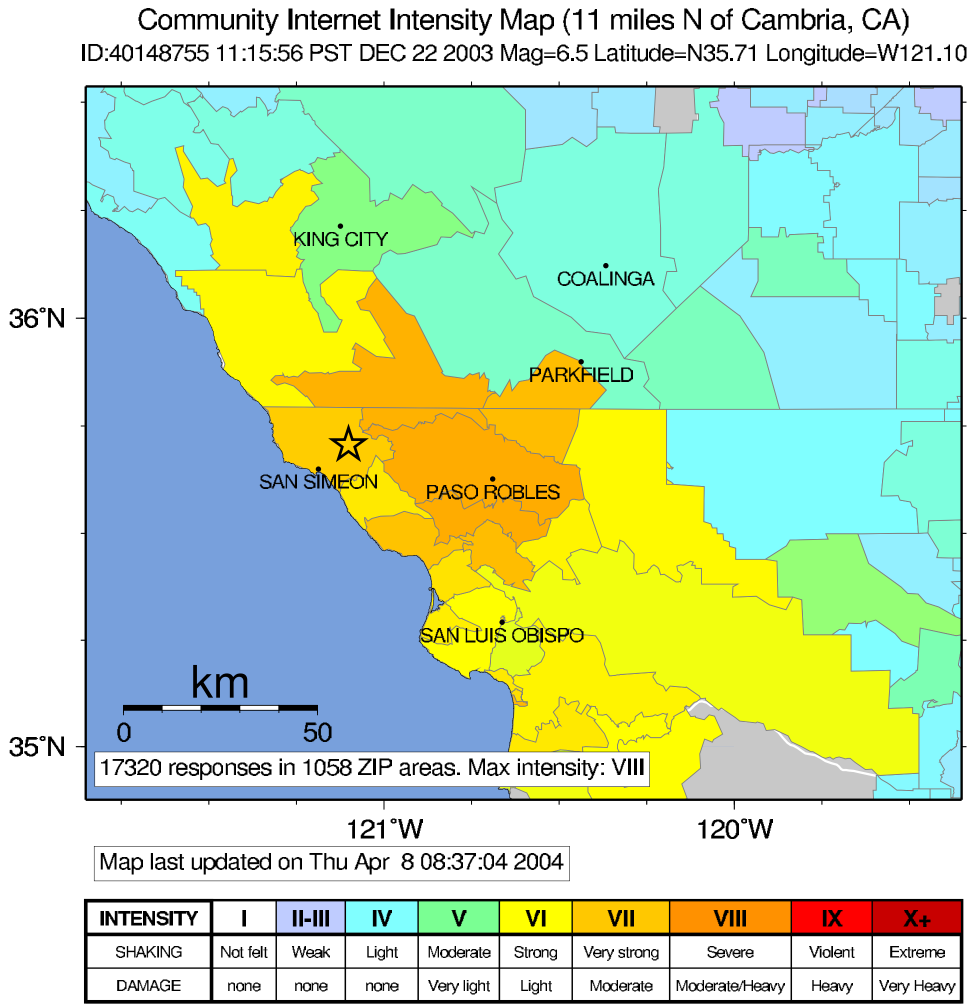


Figure 5: Close-up of the Community Internet Intensity Map for the San Simeon earthquake. *Figure courtesy of Dave Wald.*

working group is developing a model that takes into account that ShakeMaps are produced in multiple locations, with primary and backup systems, with the possible loss of communication between any of the producers. In this model, all primary and backup systems would send their products to the Web servers (or other centralized distribution points) for Web page processing. Each region would have a single authoritative system – all other systems would be considered backup systems. Maps from backup systems would only be used if maps from the authoritative system are not available. If backup maps are used, they would be replaced by the authoritative maps when and if they become available. This approach is similar to the model in the Recent Earthquake Web page, which allows multiple sources to provide earthquake information with the most ”authoritative” source selected for presentation.

Some users have raised questions about the way ShakeMap smooths data. In particular, concerns were raised about the observations at Templeton (higher than the predicted values) and Cambria (lower than the predicted values). The CISN ShakeMap working group is looking into configuration issues such as grid tension and regression fitting.

Finally, the San Simeon experience showed that some users are unfamiliar with the limitations and behavior of ShakeMap. For example, some users did not appreciate that ShakeMaps where station coverage is sparse will be less reliable, as the initial maps will be point source model estimates with limited constraining data. Some users did not realize that ShakeMaps can be updated frequently, often through the addition of data or by information about the, and that the updated maps should be used to revise response plans. Although the issue of reliability may be addressed through the efforts to grade or quantify ShakeMap quality, the confusion reflects the general need for better communication and outreach about the use of earthquake information products.

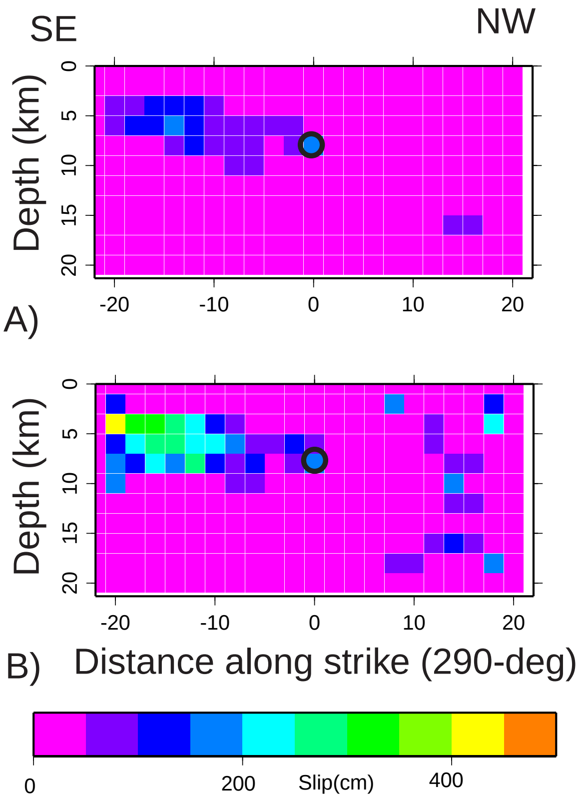


Figure 6: Comparison of slip model reported in Hardebeck et al. (2004) using 6 BDSN stations and a single time window (A) and one obtained adding seismic station PKD, GPS deformation data from two nearby sites and using 6 time windows to account for the long-period nature of the data (B) (Dreger et al, 2004). The two slip models are plotted on the same scale. The overall pattern is similar but the slip amplitude nearly doubles in (B). *Figure courtesy of D. Dreger.*

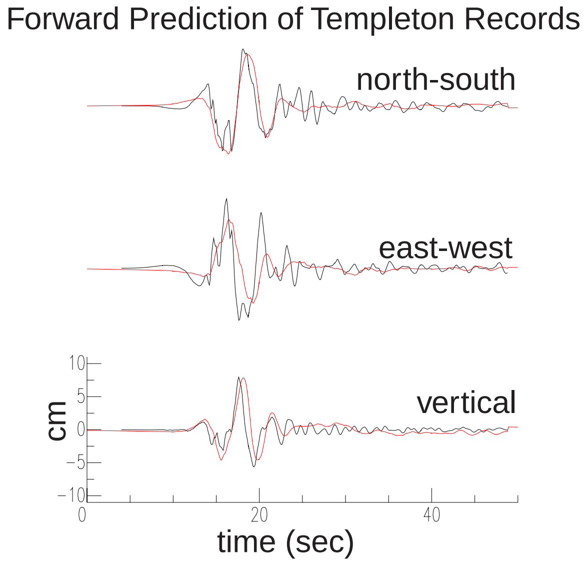


Figure 7: Comparison of three-component displacement records (black) at the Templeton Hospital site, and predicted displacement records (red) using the slip model shown in (B) above (Dreger et al., 2004). The Templeton records were not used to derive the slip distribution. The hard rock synthetic seismograms (Vs=1500 m/s) were scaled up by a factor of 1.62 to account for the 400 m/s shear-wave velocity at the Templeton NEHRP class C-D site. *Figure courtesy of D. Dreger.*

Finite Source Parameters

The San Simeon event provided an opportunity to test the automated determination of finite-fault parameters implemented at the NCMC. These codes have been online since early 2001, but the only previous test of any significance was the M5.5 earthquake near Portola, CA in August 2001. While the San Simeon earthquake illustrated some shortcomings, it also provided the opportunity to demonstrate the value of source finiteness and directivity information to rapidly characterize near-fault ground motions and to augment ShakeMaps.

The finite-fault processing is implemented in several stages (Dreger and Kaverina, 2000) The first step is to test the two possible fault planes obtained from the moment tensor inversion over a range of rupture velocities by performing a series of inversions using a line-source representation. Once determined, the next stage combines the results of the line-source inversion with the directivity-corrected attenuation relationships of Somerville et al. (1997) to simulate ground motions in the near-source region. The predicted ground motions can be incorporated in ShakeMap updates.

Once the line source computations are completed, the second component of the finite-fault parameterization uses the best-fitting fault plane and rupture velocity to obtain a more refined image of the fault slip through a full two-dimensional inversion. If line-source inversion fails to identify the probable fault (due to insufficient separation in variance reduction), the full inversion is computed for both fault planes. Once completed, the near-fault strong ground motion parameters are simulated by convolving the velocity structure response with the finite-fault slip distribution. As with the line source results, peak ground motions are computed for a grid of pseudo-stations in the vicinity of the epicenter that can be incorporated in the ShakeMap system.

The automatic finite fault codes performed correctly, although a configuration mistake caused the inversion to use the lower quality of the two moment tensor solutions obtained. As a result, the finite-fault system did not obtain optimal results. The computations proved to be relatively fast in this implementation, with the line source inversion completed approximately eight minutes after the event occurred and the resulting predicted ground motions available six minutes later. The 2-D inversion and the predicted ground motions were completed 30 minutes after the earthquake.

Although the automated system had a configuration error, the processed data were available for rapid review by the seismic analyst. Using available strong motion and broadband displacement waveforms, both line-source and planar-source analyses indicated that this event ruptured nearly horizontally to the SE from the epicenter (Figure 6a), essentially in the null-axis direction of the NE dipping reverse mechanism. Because of this nearly horizontal, along dip rupture, it was not possible to uniquely determine the causative fault plane, although there was a slight preference for the NE dipping plane which is consistent with aftershock distribution. The southeast rupture produced directivity-amplified ground motions toward the SE that is consistent with felt reports and the damage in Paso Robles. The preliminary results from the reviewed finite source analysis were included in the ShakeMap system approximately 4 hours after the earthquake.

As seen in Figure 3c, the addition of information about the fault length and orientation was an important addition to the ShakeMap, particularly given the sparseness of instrumentation. This methodology provides an important tool in areas with limited station distribution to improve ShakeMaps.

Continued analysis of the waveform data and the addition of GPS data has led to an improved rupture model (Figure 6b), and illustrates a direction of the ongoing research and development of the CISN. The combined model shows similar slip to the preliminary model, but the slip amplitude is nearly doubled. This level of slip is consistent with the ground motions observed at Templeton - Figure 7 shows the ground motions predicted from this model for the Templeton station, which was not used in the inversion.

Directivity contributed significantly to the strong shaking experienced during the San Simeon earthquake. However, it is important to note that the directivity focusing was actually less than it could have been. In fact, the directivity focusing was minimized because the rupture was to the southeast along the strike of the fault plane while the slip direction was perpendicular to the fault plane. Figure 8 illustrates this by comparing estimated peak ground velocity from the finite source model (Figure 8a) with one in which the same spatial and temporal slip distribution was used but with a vertical strike-slip fault (Figure 8b).

The method of Dreger and Kaverina (2000) was used for these simulations and for the strike-slip case, only dip and rake of the mechanism were changed. The simulations show that an identical earthquake (in terms of seismic moment and slip distribution) with a strike-slip mechanism would have generated peak ground velocity motions that are 2-3 times larger than the actual dip-slip case in some areas. More telling is the fact that the area that would have experienced greater than 10 cm/s peak ground velocity would have been 4 times larger, extending significantly to the southeast.

In 1952 the Bryson earthquake occurred nearby the recent earthquake and studies (Dehlinger and Bolt, 1987) have shown that its focal mechanism was predominantly strike-slip demonstrating that the region is at risk from both reverse and strike-slip events.

Internet Quick Report

In the CISN, strong-motion data for engineering applications are distributed after major earthquakes through the Engineering Data Center via the Internet Quick Report (IQR). Data from the San Simeon earthquake were initially made available through the Engineering Data Center at `http://www.cisn-edc.org` at 12:30 on the day of the earthquake, with updates as additional data became available.

The San Simeon earthquake was recorded at more than 100 strong motion stations to distances of over 300 km, though with relatively few stations at less than 50 km. The Internet Quick Report lists the 98 records recovered so far and their peak values and distances. It also provides links to station information and allows users to download digital data. Many of the strong motion stations that recorded this earthquake are the early film recorders, and the films have been developed and scaled. For film records, only peak accelerations are listed.

The three stations closest to the epicenter recorded peak ground accelerations of 0.48 g at Templeton, 0.18 g at Cambria and 0.12 g at San Antonio Dam. The largest recorded shaking was at a 1-story instrumented hospital in Templeton, about 38 km SE of the epicenter and approximately 16 km from the projected southern end of the rupture (Figure 9). The record at the 1st floor of the Templeton Hospital and response spectra compared to 1997 Uniform Building Code (UBC) are shown in Figure 10. The data shows strong directivity in the direction of the rupture propagation, from the epicenter toward the ESE (toward Templeton). A peak value of 1.3 g was recorded at the roof of the hospital (1-story, wood-frame construction). Little damage was observed in the hospital, an important outcome. The ground level shaking at the hospital is a good indication of the shaking in the vicinity, because the hospital is small and light. The ground station in the parking lot was not operational at the time due to construction work at the hospital. The station is operational once again, and newly obtained records of aftershocks at the ground station demonstrate higher (up to 15 or 20%) motion than at the first floor of

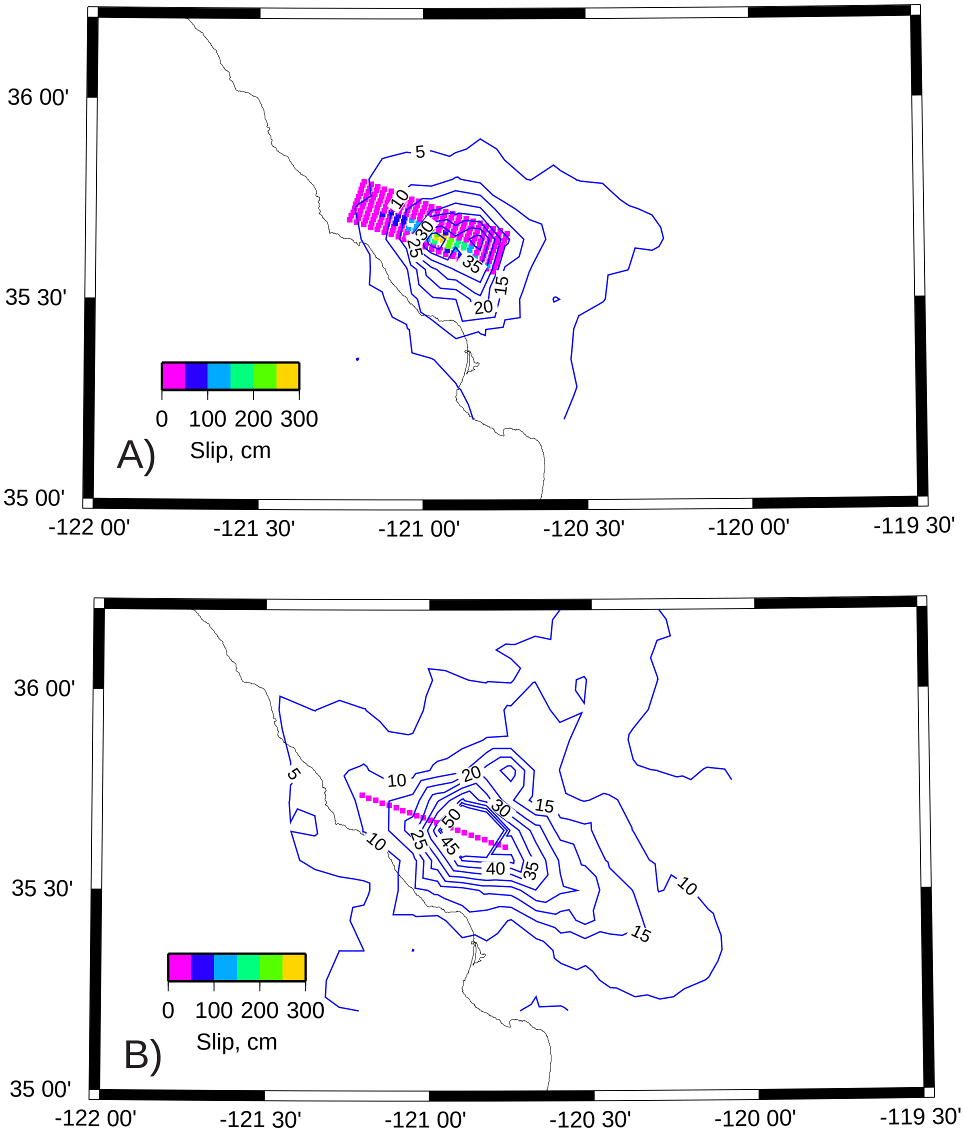


Figure 8: A) Simulated peak ground velocity (PGV) for the finite-source model shown in Figure 6b and obtained by inversion of both seismic waveform and GPS data. The surface projection of the fault slip is shown in color. The simulated PGV was computed from the geometric mean of the peak value from each horizontal component over a dense grid of stations over the fault plane. The minimum shear-wave velocity in the model used to compute the Green's functions was 1.5 km/s and therefore the simulated PGV are rock motions. The PGV is contoured in 5 cm/s intervals. B) Simulated PGV for the finite-source model in which the spatial and temporal distribution of slip on the fault plane is held fixed but the orientation of the plane is changed so that it is a NW-SE striking, vertical strike-slip fault. The southeast propagating rupture parallel to the slip direction in B) maximizes the directivity effect, while the southeast propagating rupture perpendicular to the slip direction in A) minimizes the directivity effect. *Figure courtesy of D. Dreger.*

the hospital. This suggests that the peak ground acceleration at Templeton may have reached .55 or .6 g. Templeton is about 10 km from Paso Robles, where significant damage occurred. Some of the next closest records are from the Parkfield area, with peak acceleration of 0.23 g at the Cholame 12W station.

A comparison of the attenuation of the peak acceleration data with distance to the fault with that predicted by the Boore-Joyner-Fumal (BJF97) attenuation relationship (Boore et al., 1997) is shown in Figure 11. The distances range from 12 km, for the Cambria station, to many stations at distances of over 250 kilometers.

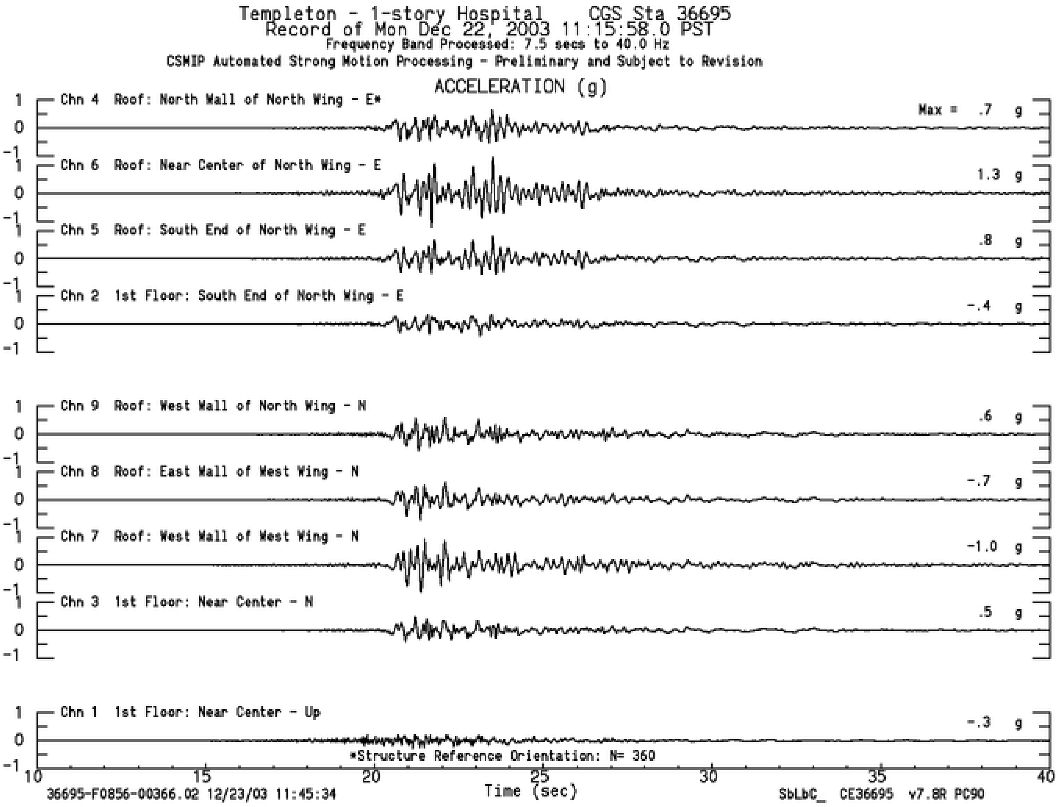


Figure 9: Acceleration, velocity and displacement recorded at the 1st floor of the one-story Templeton Hospital.

The data shows reasonable agreement with BJF97 in its applicable range (Coefficients for a reverse fault and an average shallow Vs of 700 m/sec were used; the thin line indicates distances beyond the authors' suggested limit of 80 km). Beyond that, higher attenuation with distance than predicted by the extrapolated BJF97 curve is indicated. These new data, and other recent data from digital instruments, allow extending the existing relationships to greater distances.

The point above the BJF97 curve at about 16 km is Templeton, which had 0.48g, the largest value recorded in this earthquake; lying above the curve is consistent with directivity-increased shaking in the rupture direction. The two closest stations, Cambria and San Antonio Dam, both plot below the curve, consistent with directivity-reduced values in the direction away from the rupture. More detailed information about the near fault shaking is not available for this event because of the lack of stations.

Information Distribution

Information about the event (location, magnitude, mechanisms, probability statements, and ShakeMap) was distributed through the Web pages, CISN Display, email, and cell phones/pagers. Overall, information was distributed quickly and widely through a variety of channels, although a number of small problems were noted.

Web

Problems with a firewall recently implemented by the USGS in Reston, VA, created access problems for some users trying to reach the Recent Earthquakes and ShakeMap Web pages retrieved through Akamai. The holidays and the attendant vacation schedule exacerbated this problem, which was not fully resolved until early January.

This problem was partially alleviated by the recently installed CISN Web servers. In November, the CISN Web site was brought up on a new server. In order to improve the reliability of the Web service, the site is now mirrored in northern and southern California. The CISN Web servers (`http://www.cisn.org`) offer direct access to Northern and Southern California ShakeMaps, complementing other access points.

Another recent development of the CISN available at the time of the earthquake was the myCISN Web site (`http://eoc.cisn.org`), which is a prototype site for

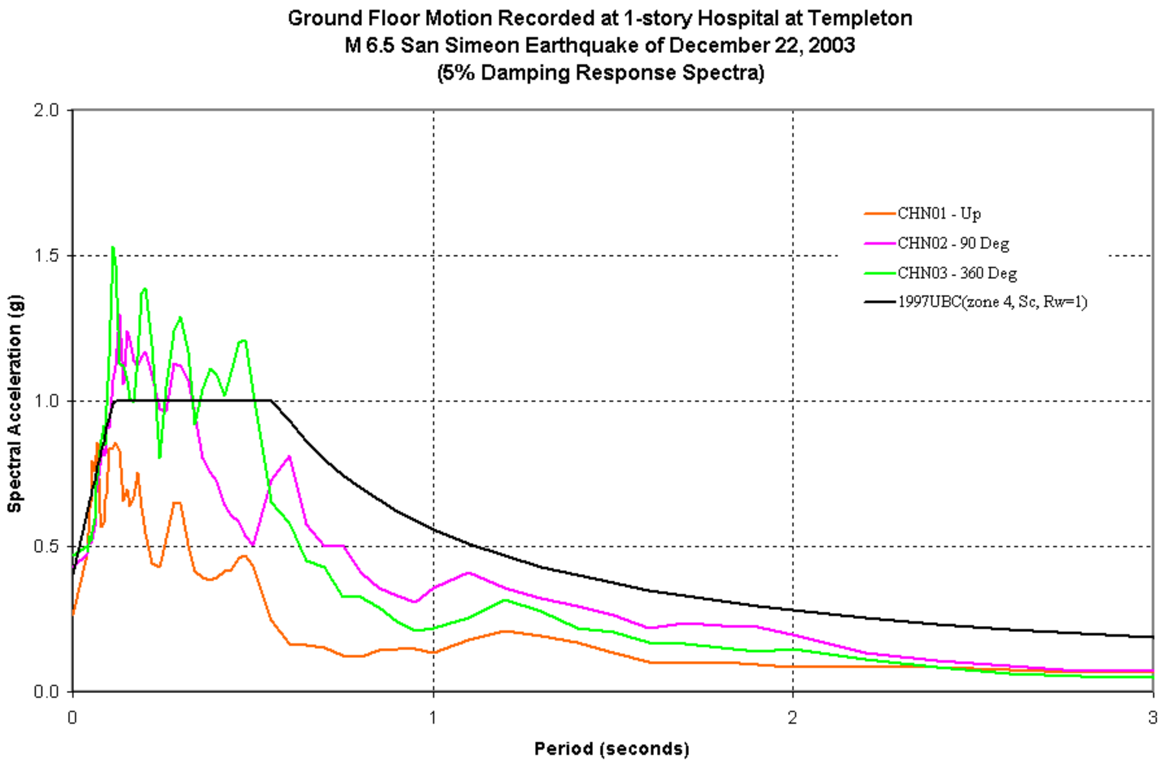


Figure 10: Response spectra (5% damping) for the 1st floor channels of the Templeton Hospital with the 1997 Uniform Building Code (UBC) spectrum for reference.

emergency responders. This system was also moved to a new computer in November, and was set up as a secure server. Although this is currently limited to a single system, there are plans to establish a mirror system in the coming year. The myCISN Web site also provides another source for access to ShakeMaps.

The proximity of the earthquake to the holidays complicated the effort to compile information and make it available online. The USGS generated a special event page shortly after the earthquake, with basic information and links to the ShakeMap, Community Internet Intensity Map, and other products. The CISN special event page went online on December 23rd, with the basic links plus information about the finite-source modeling. The CISN preliminary report on the earthquake was brought online on December 24th.

CISN Display

The San Simeon M6.5 earthquake provided a limited performance test of CISN Display and related QuakeWatch server. CISN Display is a real-time, interactive Graphical User Interface (GUI) that dynamically displays seismicity and earthquake hazards information. Unlike distribution over the Web, which requires users to visit particular sites in order to find the information they need, the QuakeWatch server pushes information to CISN Display and can actively alert users to events of interest.

At the time of the earthquake, CISN Display was being used by approximately 100 clients as part of a beta-test of the software.

The automated notification of real-time event information (origin time, location and magnitude), availability of URL's for relevant earthquake hazards information (ShakeMaps, felt reports, focal mechanism, waveforms, aftershock forecasts, etc.), and the automatic download and display of ShakeMap shape files on the GIS interface were operational

Most agencies who responded with feedback indicated that the San Simeon earthquake did not directly impact their organizations infrastructure, or it was not in their area of responsibility. However, many agencies used the San Simeon earthquake as an opportunity test their response plans (Tognazzini, 2004). Several agencies reported that CISN Display would have been used to help them to quickly determine the location and severity of the earthquake; formulate an inspection priority list based on the shaking distributions provided by ShakeMap; and rapidly allocate personnel and resources to areas most

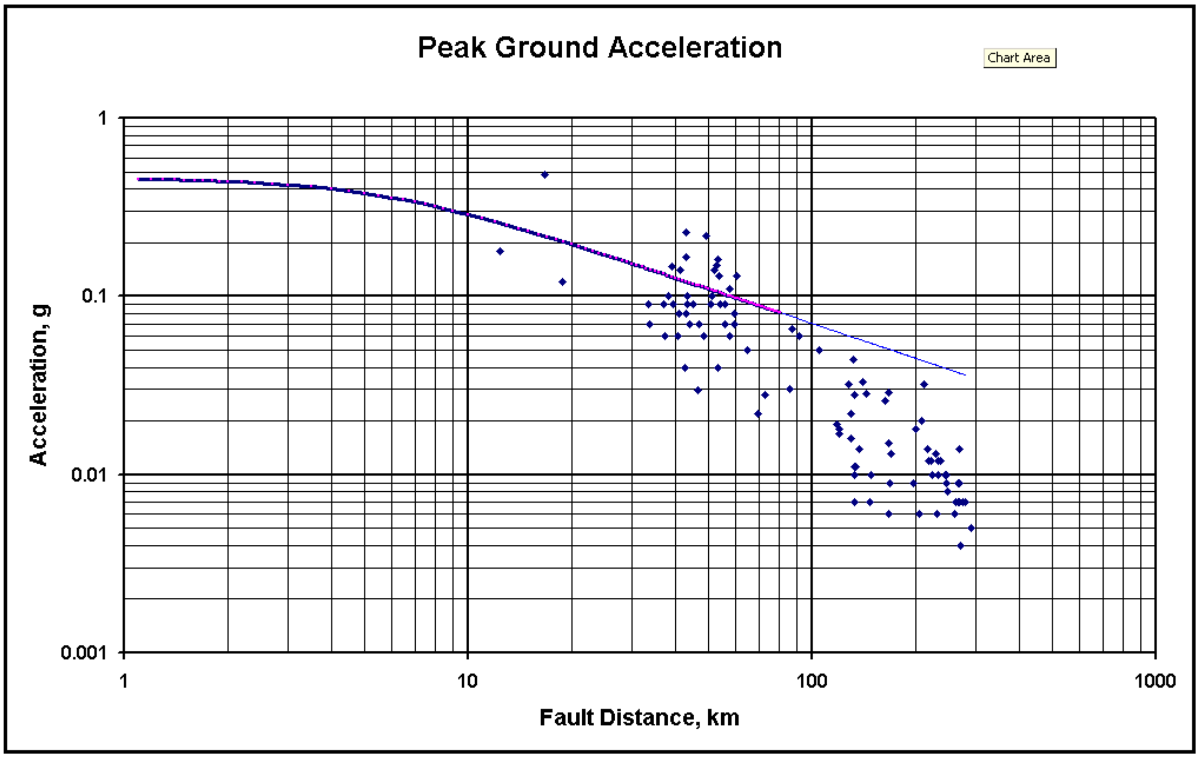


Figure 11: Peak horizontal ground acceleration plotted against distance to the fault, and the Boore-Joyner-Fumal (BJF97) attenuation relationship (Boore et al., 1997). The data shows reasonable agreement with BJF97 in its applicable range out to 80 km. Beyond that, higher attenuation with distance than predicted by the extrapolated BJF97 curve is indicated (the thin line indicates distance beyond the suggested limit). *Figure courtesy of V. Graizer.*

likely affected. Additionally, some agencies added to the "reference locations" file, a list of critical infrastructure sites vital to their organization. This allows individual agencies to quickly determine if an event is near their facilities. This configurability will also prove useful when the upcoming e-mail client becomes available with the CISN Display; it will allow organizations to produce region specific pages and e-mails with earthquakes referenced from their organization's infrastructure, and not just the nearest city.

While CISN Display performed well on many levels, one shortcoming noted by multiple users was the overlapping of numerous ShakeMaps, generated by the subsequent aftershock sequence in the immediate region. The overlapping ShakeMap layers caused some confusion among emergency managers/critical users, as it made management of the ShakeMap layers cumbersome, and tended to drain computing resources by way of downloading and plotting every ShakeMap that became available. A plan has been drafted to address this issue, which will implement magnitude and distance-from-origin constraints to govern the automatic download and display of ShakeMap shape files.

It should be noted that only about 100 clients were running at the time of the San Simeon earthquake, so while there were no reports of client-to-server connection problems, this does not represent a real-world test of the system. However, preliminary testing in the lab indicates that $\tilde{1}000$ clients per server is a safe limit.

Email and paging

A few weeks before the M6.5 earthquake, the CISN brought the first draft of an email notification signup online. The USGS has offered separate email signups for northern and southern California for sometime, but the CISN signup is the first stage in trying to create a unified and flexible subscription capability for the entire state. While the rapid distribution of earthquake location, magnitude, and the availability of ShakeMap was generally successful, it was clear that the flood of email and text messages generated by the numerous M3 and larger aftershocks overwhelmed recipients. Because of the current situation where the notification can be issued either from the USGS or CISN, it was difficult for users to remember where to unsubscribe. The CISN partners are currently designing a new email subscription service that will address these issues, as well as provide greater flexibility in notification region and magnitude threshold.

As an additional complication, although some users were troubled about the amount of email and other notifications they were receiving, it was clear that the CISN needs to consider new and/or improved ways to handle ShakeMap notifications. Some users were not aware that the ShakeMaps were changing with time and continued to use early versions of the map days after the earthquake. The mix of real-time and non-real-time stations in the CISN means that ShakeMaps will evolve in the first hour and quite possibly in the first few hours-to-days after an event. The CISN ShakeMap working group is examining issues of notification following significant changes.

Aftershocks

The San Simeon earthquake has been followed by a vigorous aftershock series, similar to that observed following the M6.4 Coalinga earthquake in 1983.

As part of the response to the event, the NCMC issued a statement of aftershock probabilities 12 minutes after the earthquake and then again approximately 24 hours later, based on the decay rate of the aftershock activity. The probabilities are largely derived from a "generic" earthquake, so the estimates early in the sequence are only a guideline. According to the aftershock forecast, there was a 90% chance of a magnitude 5 or greater quake in the first 7 days. The largest event to occur in that period was a 4.9. We also forecast approximately 120 to 200 magnitude 3 to 5 quakes in the first week. We continue to process the data, but at the time of this report we have detected 139.

Following the San Simeon mainshock, both the USGS Menlo Park and the Berkeley Seismological Laboratory experienced separate and independent problems with telemetry on leased circuits in Parkfield. It did not significantly affect reporting of earthquake activity and all data were ultimately recovered. However, subsequent to the leased line problems, the BSL has experienced problems with radio communications in the Parkfield area which limits the availability of high sampling rate data. The loss of the nearest broadband station (PKD) appears to have introduced some bias in the automatic estimation of M_L for events in the M3-3.4 range. These magnitudes will be recalculated as part of the post-processing.

The aftershock series has also created difficulties for the borehole network in Parkfield operated by the BSL. Prior to the San Simeon earthquake, this sensitive network detected 7-10 small earthquakes a day. Designed to monitor microseismicity on the San Andreas fault, the network triggered on over 20,000 events in the first two weeks after the mainshock. Preliminary analysis indicates that the triggers are overwhelmingly from the San Simeon sequence, although a portion is likely due to local events on the San Andreas fault at Parkfield. Analysis suggests that the borehole network is recording San Simeon earthquakes well below magnitude 0.0, despite its location 45 km away from the rupture.

Seismological and Engineering Data Archives

In response to the San Simeon earthquake, the Northern California Earthquake Data Center (NCEDC) had modified its normal archiving procedures in order to retain high frequency data of interest. Continuous data from the Berkeley Digital Seismic Network of broadband and strong motion sensors was archived for channels at 100 or 80 samples per second for the seven days from 12/21/2003-12/27/2003. This complements the normal continuous archive at 20 samples per second and lower. The NCEDC is also currently archiving continuous data from the High Resolution Seismic Network in Parkfield at 250 samples per second. This continuous archiving of HRSN data will continue until the the triggering level drops to a reasonable level.

Event data from the USGS Northern California Seismic Network (NCSN) are available through the NCEDC. Currently, there data are not merged with data from the Berkeley Digital Seismic Network, although the NCEDC is involved in an ongoing effort to make NCSN waveform data available in SEED (Standard for the Exchange of Earthquake Data format. When completed, nearly all data from the NCEDC will be available with the same set of tools.

The location of this event in central California meant that it was also well recorded by the Caltech/USGS network in southern California. In response, the Southern California Earthquake Data Center (SCEDC) also modified their normal procedures to archive continuous data from their broadband and strong motion sensors from six hours before the event through twelve hours after. One of the issues the CISN may address in the coming months relates to enhancing access to the NCEDC and SCEDC archives. Events such as San Simeon, which are well recorded throughout California, provide motivation for common interfaces as well as merged data sets.

The data analysts at the NCMC are reviewing the earthquake data as fast as possible, but the rate of aftershock activity has created special challenges. In the first few days of the sequence, the data is quite difficult to process because aftershocks often occur at two different locations nearly simultaneously which confuses both the automated systems as well as humans. As of April 12, 2004 analysts have reviewed 64% of the 5206 detected events. More than 380 first-motion mechanisms and 13 moment tensor solutions have been generated.

The CISN Engineering Data Center allows engineers and seismologists to view and download the strong-motion data and get information about the station that registered the earthquake. The most recent data can be accessed via the Internet Quick Report (as described above) with other data available through either the Internet Data Report or a Search for Data facility. An Internet Quick Report is generally prepared for earthquakes over magnitude 4.0, for which a ShakeMap is also released by CISN. The content of the IQR after an earthquake expands as new data continues to be recovered.

For the San Simeon event only data from the strong-motion programs (CGS/SMIP and USGS/NSMP) is included at present. The NCMC and SCMC are using this event to complete testing and validation of programs that convert data into the V0 format used by the Engineering Data Center . A CISN Standards working group is currently developing plans for automatically generating V0 files for data recorded by the Northern and Southern California Management Centers.

Response

The California Office of Emergency Services (OES) is a partner to the CISN and a primary recipient of earthquake information products. For OES, knowing the location and distribution of ground motions within the first few minutes after the event is valuable to understand the scale of the earthquake and to mobilize an appropriate response. In the case of the San Simeon earthquake, OES and state agency staff received pager and REDI-CUBE notification of location and magnitude and downloaded initial ShakeMaps when they became available. The State Operations Center (SOC) and Southern Regional Emergency Operations Center (EOC) were notified and briefed, and then activated.

OES convened a conference call with CISN scientists at 12:00 (40 minutes after the earthquake) to assess the earthquake and possible implications. Discussions continued through the afternoon concerning the causative fault, probability and migration of aftershocks, and potential for additional events. This information was passed on to Operational Areas through the Southern Region EOC, to the Director of OES and to the Governor's Office.

Loss Estimation

As part of the CISN operations, ShakeMaps are automatically distributed to OES and other agencies. OES is currently working to automate HAZUS operation based on the distributed ShakeMaps and a computer system to distribute the HAZUS (NIBS, 1999; Kircher et al., 1997a; 1997b) processing is being configured.

At the time of the San Simeon earthquake, however, HAZUS runs were not automated. As soon as notification of the event and the initial ShakeMap were posted, OES staff computed the first HAZUS estimate of losses for San Luis Obispo county. The first run was available within one hour of the event and provided input to decision makers. As new ShakeMaps were posted and information was received from impacted counties, the HAZUS runs were updated and expanded to include Santa Barbara county. OES Coastal region was the designated HAZUS lead for this event with concurrent runs performed in other regions for backup and verification.

The San Simeon earthquake also provided the opportunity to examine the sensitivity of HAZUS to the evolution of the ShakeMaps. OES performed a series of runs with HAZUS 99 for San Luis Obispo county, using a representative selection of ShakeMaps over time. Table 3 summarizes the changes in results for one modeled loss component. The HAZUS estimates show significant variation, from an initial estimate of \$30 million immediately following the event to the January 5th estimate of \$279.3 million to \$325.4 million for the March 24th update. For comparison, a HAZUS run using the magnitude, the fault orientation, and the Boore et al. (1997) attenuation relationship for a reverse mechanism yields an estimate of \$179.2 million.

The modeled results change significantly at several points in the evolution of the ShakeMaps. The first estimate is based on limited data with a point source approximation. The second estimate more than doubles the loss when information about the linear extent of the source is added. The addition of the observations from Templeton raises the losses by nearly a factor of 4.5, due to the influence of the close-in station on the ShakeMap. The change in the next few maps is more modest, as more stations are added and as the ShakeMap bias is modified. The revision of the ShakeMap on March 24 with the ground motions corrected for the erroneous distance calculation raises the loss again, as higher ground motions are predicted in the near fault area.

In general, one would expect a good correlation between the HAZUS model and the run based on the finite-fault information at 15:33. During each run, ShakeMap fits a regression to the data in order to identify outliers and to allow the data to "drive" to model. At the time of the 15:33 ShakeMap, the closest station was over 40 km away. In this case, the more distant stations had lower values and the regression fit lowered or reduced the ground shaking compared to what would be expected from an M6.5. With the addition of Templeton, the observation of high shaking levels raised the bias over what one would expect from an M6.5.

Many of the HAZUS loss estimates are based on demographic and building-related data aggregated at the census tract level. In order to make use of ShakeMaps, HAZUS determines the ground motion (using PGA, PGV, 0.3 and 1 second spectral acceleration values from ShakeMap) at each census tract centroid. Typically, in urban areas, census tracts are small and this effective resampling of the ShakeMap inputs doesn't greatly affect the results, as the ground motion variation within one census tract should be relatively small. However, in more rural areas, large census tracts may include a larger range of geology, soil conditions, and ground motion values. Only that value at the centroid of the census tract is used by the model to estimate losses for the exposure in the entire census tract. In the case of the San Simeon earthquake, most of the census tracts are relatively large. Thus, as the ShakeMap inputs were refined over time, they affected the values used to model the losses and therefore the HAZUS model output. In particular, one census tract centroid lies directly over the midpoint of the fault segment and thus was extremely sensitive to the revision on March 24th.

HAZUS Sensitivity Tests	
ShakeMap Time Stamp	Building-related Economic Loss (Millions)
12/22/2003 11:24	$30.5
12/22/2003 15:33	$64.1
12/22/2003 18:34	$290.0
12/23/2003 16:28	$264.4
01/05/2004 09:18	$279.3
03/24/2004 16:00	$325.4

Table 3: Comparison of the estimates of building-related economic loss from HAZUS runs based on the selected sequence of ShakeMaps. Refer to Figures 3 and 4 for maps. HAZUS runs courtesy of Johanna Fenton of OES.

Conclusions

Large earthquakes like the San Simeon M6.5 event provide unique opportunities for seismic networks to test their software and systems. Unlike smaller quakes which occur on a regular basis, large quakes test design assumptions, systems throughput, and rarely implemented algorithms. When these quakes occur in sparsely instrumented regions, the assumptions become even more tenuous. This earthquake illustrated those features of the CISN that performed as designed, but also indicated where more work is needed.

The one component of the CISN that will be difficult to rectify quickly is the lack of digital stations in the vicinity of the earthquake. This compromised the quality of the ShakeMaps for the mainshock and aftershocks, as well as posing limitations in our ability to obtain reliable locations and magnitudes for the smaller events. Recent efforts to modernize seismic networks from the ANSS and TriNet projects have focussed on improvements in urban areas of the state. While this approach is clearly warranted due to the high risk to life and structures, the amount of resources to fully instrument all areas of high seismic hazard will require a considerable investment of resources.

Because technological changes occur at such a rapid pace, networks like the CISN constantly find themselves responding to unanticipated situations. Unlike previous quakes where public demand for information on the Internet overwhelmed CISN and ANSS webservers, during this quake we were able to satisfy most requests as a result of the Akamai web-hosting service. However, unknown errors in firewall configurations did compromise information delivery. We respond to these challenges as fast as we can, given the resources at our disposal, but technical changes, failures of the public infrastructure that carries our information, and flaws in seismological software or configurations exposed only during rare quakes makes flawless and accurate delivery of seismological information extremely challenging.

The good news is that we learn more with every earthquake. For the first time automatically generated ShakeMaps were used in HAZUS loss estimate software to guide emergency response activities. Reliable products like moment magnitudes are now routinely and automatically computed, such that inaccurate estimation of earthquake size is no longer an issue. Cutting-edge seismological products like finite-fault estimates of slip distribution are now rapidly integrated into ShakeMaps. Products like CISN Display enable us to push our information into the hands of users who need authoritative information in real time. Our information is available almost immediately at data centers on the Internet, so that sophisticated users like engineers and seismologists can begin their research on the earthquake and its effects on the built environment. The effort continues, but the San Simeon M6.5 quake illustrates how ANSS networks like the CISN are working to rapidly aid the public in assessing and responding to damaging earthquakes.

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Related Links

`http://www.cisn.org/` - CISN Web server. Now includes direct access to ShakeMaps for California earthquakes.

`http://www.cisn.org/special/evt.03.12.22/` - CISN report on the San Simeon earthquake. Reports on events of interest are generally posted to the CISN Web site within 24 hours.

`http://docinet3.consrv.ca.gov/csmip/cisn-edc/IQR/SanSimeon_22Dec2003/iqr_dist.htm` - Internet Quick Report from the CISN Engineering Data Center for the San Simeon earthquake.

`http://www.cisn.org/services/signup.html` - Prototype CISN signup page for earthquake and ShakeMap notification. This is first draft and already there are efforts to improve the interface and provide greater flexibility for the user.

`http://eoc.cisn.org/` - Pilot Web server for My-CISN, designed for emergency responders.

`http://www.anss.org/` - Web site of the Advanced National Seismic System.

`http://earthquake.usgs.gov/` - Web site of the USGS Earthquake Program. Provides access to information about recent earthquakes, including ShakeMaps and the Community Internet Intensity Maps.

References

Boore, D. M., W. B. Joyner and T. E. Fumal, Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work, *Seismol. Res. Lett., 68*, 128-153, 1997.

Dehlinger, P., and B. Bolt, Earthquakes and associated tectonics in a part of coastal central California, *Bull. Seis. Soc. Am., 77*, 2056-2073, 1987.

Dreger, D., Lombard, O., Boatwright, J., Wald D., and L. Gee, Finite source models of the December 22, 2003 San Simeon earthquake and applications to ShakeMap (abstract), *Seismol. Res. Lett., 75*, 293, 2004.

Dreger, D. and A. Kaverina, Seismic remote sensing for the earthquake source process and near-source strong shaking: A case study of the October 16, 1999 Hector Mine earthquake, *Geophys. Res. Lett., 27*, 1941-1944, 2000.

Earthquake Engineering Research Institute, Preliminary observations on the December 22, 2003, San Simeon earthquake, `http://www.eeri.org/lfe/usa_san_simeon.html`, 2004.

Hardebeck, J., Boatwright, J., Dreger, D., Goel, R., Graizer, V., Hudnut, K., Ji, C., Jones, L., Langbein, J., Lin, J., Roeloffs, E., Simpson, R., Stark, K., Stein, R., and J. Tinsley, Preliminary report on the 22 December 2003 M6.5 San Simeon, California, earthquake, *Seismol. Res. Lett., 75*, 155-172, 2004.

Jennings, C.W., Fault activity map of California and adjacent areas, with locations and ages of recent volcanic eruptions: *California Division of Mines and Geology, Geologic Data Map No. 6*, map scale 1:750,000, 1994.

Kircher, C., A. Aladdin, A. Nassar, O. Kustu, and W. Holmes, Development of building damage functions for earthquake loss estimation, *Earthquake Spectra, 13*, 663-682, 1997.

Kircher, C., R. Reitherman, R. Whitman, and C. Arnold, Estimation of earthquake losses to buildings, *Earthquake Spectra, 13*, 703-720, 1997.

McLaren, M., and W. Savage, Seismicity of South-Central Coastal California: October 1987 - January 1997, *BSSA*, *91*, 1629-1658, 2001.

National Institute of Building Science (NIBS), HAZUS Technical Manual, Developed by the Federal Emergency Management Agency through agreements with the National Institute of Building Science, Washington, DC, 1999.

Somerville, P., N. Smith, R. Graves, N. Abrahamson, Modification of empirical strong ground motion attenuation results to include the amplitude and duration effects of rupture directivity, *Seismol. Res. Lett., 68,* 199-222, 1997.

Tognazzini, R., The ravings of an earthquake engineer, acting as an emergency responder during the M6.5 San Simeon earthquake, `http://www.cisn.org/special/evt.03.12.22/tognazzini.pdf`, 2004.

Wald, D., V. Quitoriano, T. Heaton, H. Kanamori, C. Scrivner, and C. Worden, TriNet "ShakeMaps": Rapid generation of peak ground motion and intensity maps for earthquakes in southern California, *Earthquake Spectra, 15*, 537-556, 1999a.

Wald, D., V. Quitoriano, L. Dengler, J. Dewey, Utilization of the Internet for rapid community intensity maps, *Seismol. Res. Lett., 70*, 680-693, 1999b.