Photo by hitchster.

Damage from the Napa earthquake of August 2014.

RESEARCH

A Few Seconds of Warning

By Margaret Hellweg

In the early morning hours of Sunday, August 24, 2014, people in the San Francisco Bay Area were jolted awake by an earthquake. Initially, nobody knew the size of the quake, where the epicenter was located, or what damage could be expected. Only a few people on watch in the offices of San Francisco's Department of Emergency Management, the Police Department of the University of California, Berkeley, and the control center for the Bay Area Rapid Transit's train system (BART) knew what was happening before they felt the shaking: an earthquake of magnitude 6.0 struck the city of Napa at 3:21 a.m., Pacific Time. These offices had the ShakeAlert User Display running on their computers and received its rapid alert prepared within five seconds of the start of the earthquake rupture and before the strong shaking started at their locations.

ShakeAlert — the earthquake early warning (EEW) system being developed and tested by UC Berkeley seismologists and their colleagues in California — is almost available as a prototype production system. With the exception of BART, current users in California are beta-testers of the system and do not yet base any actions on the alerts they receive. The prototype production system is now operational, and beta-testers will begin taking that next step.

Early Warnings in "Earthquake Country"

A similar earthquake early warning system would be of great value in Chile, one the world's most seismically active countries. Earthquakes of magnitude 8 and above strike its territory about every 10 years. These temblors and associated phenomena, such as tsunamis and landslides, have caused more than 99% of deaths and 98% of economic losses due to natural disaster since the early 1900s. As a result of the February 2010 earthquake and tsunami (Maule earthquake, magnitude 8.8), 521 people were killed, 56 remain missing, and economic losses amounted to approximately 14% of GDP.

The development of earthquake early warning in California over the past 10 years is based on data from the modern seismic and geodetic networks operated in real time in California. They have demonstrated that rapid processing can detect earthquakes when they happen and, to a great extent, not "cry wolf" by sending alerts when there is no local earthquake.

How does earthquake early warning work? Earthquakes produce two kinds of seismic waves that travel at different speeds. The primary waves (P-waves) are faster but less destructive. The secondary waves (S-waves) arrive later and produce a shearing, shaking movement that can destroy buildings and infrastructure. Both types of wave spread throughout a region, like ripples in a pond. Their amplitudes decrease with distance, although there may be secondary effects in soft sediments and basins that can result in great damage far from an earthquake's source. These effects were the cause of the considerable damage and deaths in Mexico City during the great earthquake that occurred off the country's southern coast in 1985.

If we can detect the P-waves radiating from an earthquake and determine its location and size within seconds, then we can alert people and organizations in the area that will be affected by damaging shaking before it starts. People can "drop, cover, and hold on" until the shaking stops, and automatic actions can help to prevent or reduce other problems. Take the example of BART, the Bay Area's train system. These trains are all run by a computer system overseen in BART's operations center. Since September 2013, the BART computers automatically slow all trains when triggered by an earthquake alert from ShakeAlert. The Berkeley Seismological Laboratory has been working with BART engineers for several years, first to implement the EEW feed to the operations center and then to determine which EEW alerts should trigger a train slowdown. During the 2014 South Napa earthquake, the BART systems worked effectively. Trains would have been slowed, if any had been running at 3:21 on that Sunday morning.

Most of the great earthquakes in Chile take place off the coast (see map). This location actually offers a benefit from an early warning point of view: since the time between P-waves and S-waves is longer, there is more time to prepare or take action to counter the shaking. However, these earthquakes also cause tsunamis, earthquake-generated waves that inundate the coast and damage or wash away boats, buildings, infrastructure, and also people. For distant locations — like California in the case of the Maule event — the tsunami arrives many hours after the quake, allowing considerable time to prepare. In a local event, however, the devastating wave may arrive within minutes of the shaking.

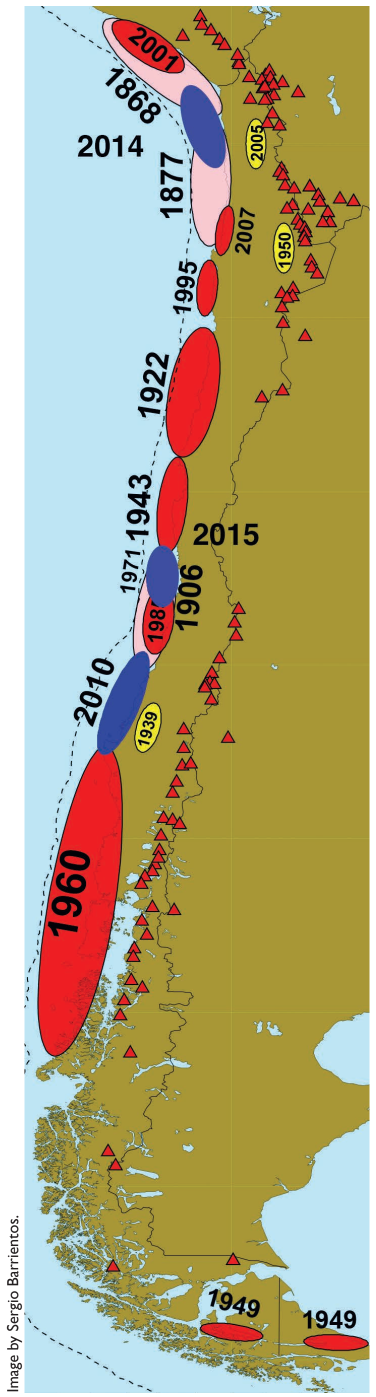

Image by Sergio Barrientos.

Chile's major earthquake history: Yellow areas are normal-faulting quakes; great thrust quakes inferred from historical records are pink; great thrust quakes instrumentally recorded from 1922 to 2007 are red, and since 2010, blue. Red triangles are active volcanoes.

Before the Maule earthquake in February 2010, the Chilean earthquake monitoring system was not capable of supporting earthquake early warning. Since then, the Chilean government has begun to modernize its earthquake monitoring system through the National Seismological Center (Centro Sismológico Nacional, CSN) at the Universidad de Chile. Data from the new stations will be able to support earthquake early warning. This project began a collaborative effort between seismologists in Berkeley and Chile to provide input and feedback on the implementation of the new network and to bring the earthquake early warning processing to Chile. When fully implemented, Chile's EEW system will be able to provide several seconds to a few minutes warning of shaking to most population centers.

Working Together to Improve Alerts

The collaboration began with a workshop at the CSN in Santiago, Chile, in early March 2015, which included participants from CSN and UC Berkeley, as well as from the German Research Centre for Geosciences (GFZ), the Hydrographic and Oceanographic Service of the Chilean Navy (Servicio Hidrográfico y Oceanográfico de la Armada de Chile SHOA), the National Geology and Mining Service (Servicio Nacional de Geología y Minería, Sernageomin), the Department of Geophysics at the Universidad de Chile, and a Fulbright scholar. Presentations on Chilean and California seismicity and monitoring networks were followed by a discussion of earthquake monitoring in

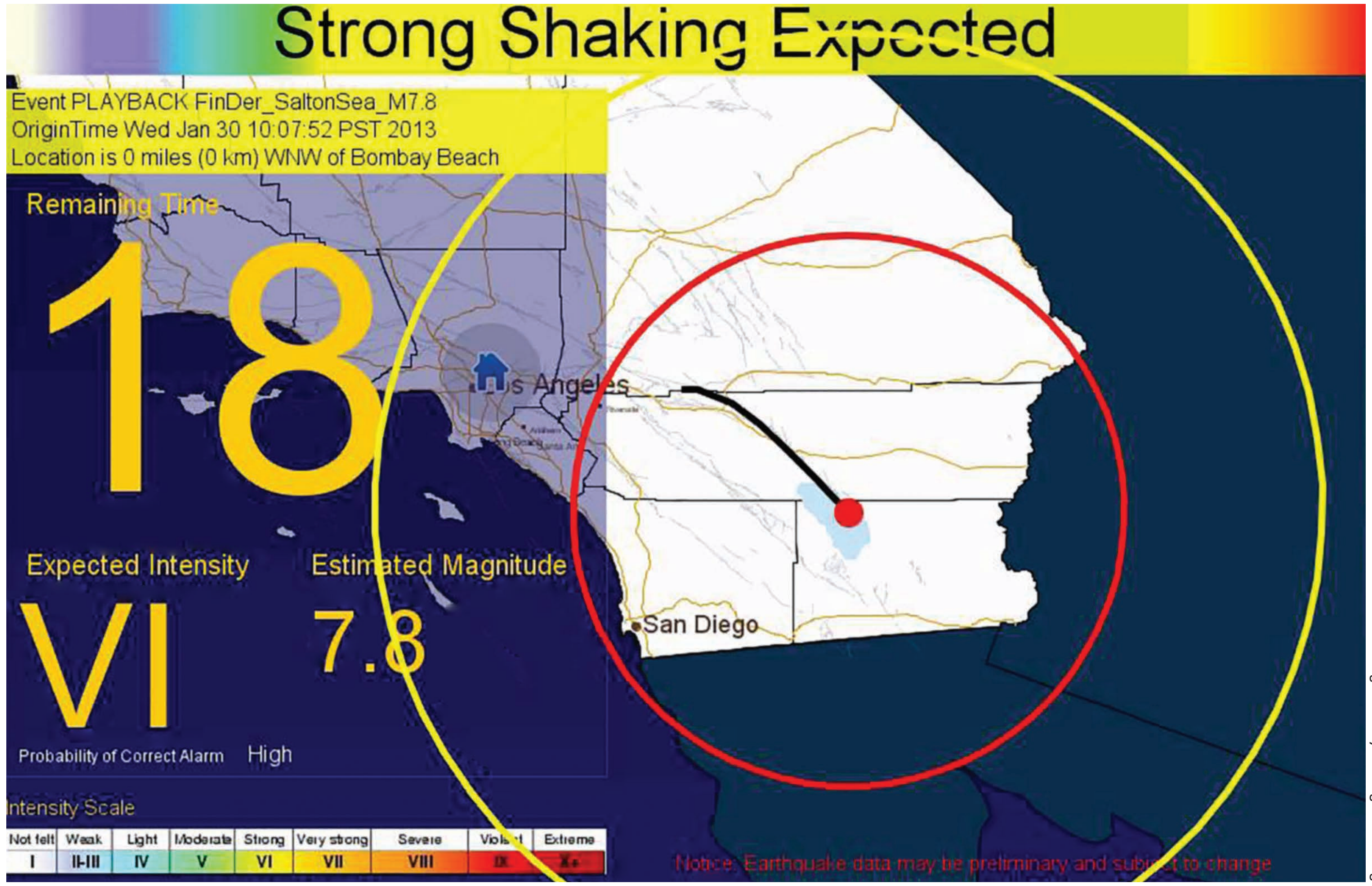

Image courtesy of Margaret Hellweg.

The ShakeAlert app shows the expected arrival time and intensity of ground movements.

general and advanced earthquake information products like the moment tensors and finite fault estimates produced at UC Berkeley. The Berkeley team then presented its algorithms based on both seismic data (ElarmS) and geodetic or GPS data (GlarmS), describing how they work and how they have performed in California.

The seismic data provides rapid information on location and magnitude. Unfortunately, experience has demonstrated that ElarmS saturates at large magnitude, which means that although an earthquake may be larger than magnitude 7, ElarmS will not be able to tell how much bigger it is. Data from GPS monitors can detect the large movements from great quakes and provide a better estimate of their magnitudes, but it takes a little more time.

The large quakes needed to test and improve the algorithms are fortunately extremely rare in California. Using data from Chile's great quakes will allow the Berkeley team to tune ElarmS and GlarmS. Having the algorithms running sooner rather than later in Chile will help the team at the CSN to gather experience with them and to work with SHOA, mentioned above, and Onemi (Chile's Office of Emergency Management) to develop operations plans that will use the early warnings to reduce both quake and tsunami damage in the next big earthquakes.

In the final session of the March workshop, we discussed instrumentation and station density requirements for an EEW system, as well as "next steps" for our project. This initial workshop was followed by individual visits to support the installation and implementation of the EEW software for ElarmS. Felipe Layton, a seismologist from CSN visited UC Berkeley in June. Ivan Henson, the seismologist in charge of the software package at UC Berkeley visited Chile in October. During these two visits, the teams exchanged information about the EEW codes, which were installed and configured on the CSN computers. For this project's final activity, UC Berkeley organized a workshop on "EEW and Subduction Zone Seismicity" in November 2015. The workshop included participation from U.S. partners, such as the United States Geological Survey, the University of Washington, and Central Washington University. The participants from these two universities are particularly interested in subduction zone earthquakes, since they are living on the Cascadia Subduction Zone.

Diego Melgar, a BSL researcher, has been particularly interested in using EEW and other data for very rapid tsunami assessment so that the population in the danger zones can be warned more quickly. The collaboration with the CSN team is extremely valuable for his work on tsunami alerting (TlarmS). Melgar has been able to access the seismic and geodetic data that has been collected from recent great earthquakes in Chile, including the Illapel earthquake that shook the coast near Santiago in September 2015. Tsunami warnings for local earthquakes are a particular challenge, as the wave may arrive within minutes of the event, and the people in the run-up zone may need to travel several kilometers to reach safety. Melgar's method uses any data rapidly available — seismic, GPS, or tide gauge — to estimate the size and location of a big quake and the expected run-up along the coast. The recent Illapel quake provided a good example: the TlarmS results produced accurate estimates that could have been used to issue warning maps in the first three minutes after the earthquake.

Reaping the Benefits for Chile & California

Both teams and countries are benefiting from the long-term collaboration initiated through this project. The Centro Sismológico Nacional of Chile is receiving support and expertise from the Berkeley Seismological Laboratory towards the implementation of earthquake and tsunami early warning systems in this extremely earthquake-prone country. ElarmS is already running in Chile. Soon, GlarmS and TlarmS also will be implemented. Experience with these tools will grow as the number of stations in Chile's seismic and geodetic networks increase, and the capacity to produce rapid earthquake and tsunami information will help warn and protect Chileans.

At the same time, the data from past and future large-to-great earthquakes in Chile will allow the Berkeley Seismological Laboratory to improve rapid estimation of earthquake parameters for large-to-great earthquakes for the operation of the EEW system in California and the West Coast of the United States.

We expect the demonstration of improvements — both in California and Chile — will encourage the investment of funds to continue the collaboration to the benefit of both partners and to continue improvements to earthquake monitoring and alerting in both countries.

The project's senior personnel are: Dr. Sergio Barrientos, Director of the Centro Sismológico Nacional of the Universidad de Chile; Professor Richard Allen, Director of UC Berkeley Seismological Laboratory; Professor Douglas Dreger, Associate Director of UC Berkeley Seismological Laboratory; and Dr. Margaret Hellweg, Operations Manager, UC Berkeley Seismological Laboratory. Seed funding for this collaboration came from a CLAS/Conicyt grant.

Researchers bury sensors outside of California Memorial Stadium on the UC Berkeley campus.

Photo by Miguel Oropeza Caballero.