Three Years of Comparative Real-Time Earthquake Early Warning Testing in California


I. Introduction

The California Integrated Seismic Network (CISN) recently concluded a three-year project (August 2006 – July 2009) aimed at the implementation, real-time testing, and comparative performance evaluation of three participating earthquake early warning (EEW) algorithms: 1) the Tau-Pm (OnSite) algorithm developed by Caltech, 2) the ElarmS algorithm developed by UC Berkeley, and 3) the Virtual Seismologist (VS) algorithm developed by the Swiss Seismological Service at ETH Zurich. These three EEW algorithms were installed and tested, and continue to run in real-time at the California Seismic Network (SCSN), the Berkeley Digital Seismic Network (BDSN), and the USGS Merlo Park network. Over the last three years, these EEW algorithms submitted real-time and automatic non-interactive offshore event reports to CISN and the USGS Menlo Park network. Based on the CISN EEW Testing Center definitions of triggers, VS has a false trigger rate of 3.5% at the M=4.0 level based on data from the last six months of testing.

II. California-wide Testing

During the three year study, all three algorithms successfully detected many earthquakes, and in some cases, predicted peak ground shaking before it occurred. Each algorithm, originally designed for a specific region of the state, was expanded to process data from throughout California, to run continuously in real-time, and to provide real-time alert messages. All three algorithms submitted event reports, containing magnitude and peak ground shaking estimates (and location estimates for VS and ElarmS) to the CISN EEW Testing Center, which compared the event reports to the CISN earthquake catalogue. Algorithm performance was evaluated on magnitude and location accuracy, as well as false and missed alerts. The CISN EEW Testing Center posted regularly updated performance summaries on its website (http://www.scieg.org/tee).

A total of statewide testing made use of 382 stations with a total of 585 broadband and strong motion instruments from the SCSN, BDSN, the Berkeley Digital Seismic Network (BDSN), and the USGS Merlo Park network. With processing facilities at Caltech/Pasadena, UC Berkeley, and USGS Merlo Park.

Figure 1: EEW algorithm performance is strongly tied to station density. All three EEW algorithms performed extremely well (95-100% detection capability at M=3.0 level) in regions with ~20 km inter-station spacing. In general, performance deglaid with decreasing station density. Above is a map of the real-time seismic stations used in EEW testing (blue, green, red squares) overlaid on a seismic hazard map. White squares are ~100 additional stations reserved to have 20 km station spacing for high resolution imaging and 40 km and 40 km station spacing along the San Andreas fault.

Table 1: Statistical error distributions for ElarmS magnitude, location, and peak ground motion estimates (derived from Japanese data)

Table 2: During the 15-month testing period, there were 230 M>3.0 events recorded by the VS algorithm.

III. OnSite Algorithm Highlights

The OnSite algorithm being implemented by Caltech uses the frequency content and amplitude information of the first few seconds of the observed P wave to estimate magnitude and peak ground motion at the same site. Over the last three years, the OnSite algorithm detected ~140 local earthquakes in California and Baja Mexico in the magnitude range 3.5 - 5.4. Most reporting delays ranged between 9 and 16 seconds and has recently reduced to 4 to 11 seconds due to software design improvements.

Figure 2: The Tau-C / Pm trigger criteria was developed to improve real-time performance of the OnSite algorithm. (a) This criteria uses Tau-C (and hence magnitude)-dependent thresholds for Pm, takes into account empirical ground motion attenuation characteristics in Southern California, and successfully removed 97% of previous false triggers on broadband stations. (b) The criteria also reduced the scatter in magnitude estimates for small earthquakes.

Table 3: The VS algorithm is a Bayesian network-based algorithm being implemented by UC Berkeley. The algorithm detects Pm-waves at several times around an event epicenter and uses arrival times, amplitudes, and frequency content of the Pm-waves to rapidly estimate the magnitude and location of the event. ElarmS then uses regional GMPEs to predict the expected peak ground shaking throughout a region in real-time.

Figure 3: Distribution of (a) observed and (b) predicted values of PGV at 80 CISN stations that triggered the OnSite algorithm during the 29 July 2009 Mw=4.0 Chino Hills earthquake. Each estimate in (b) would have been available within 3 seconds of the P wave arrival.

Figure 4: Error dependent station corrections for Tau-Pm and Pm were developed for Northern Californi (a,b), Southern California (c,d), and Japan (e,f).

IV. ElarmS Algorithm Highlights

The ElarmS algorithm is a network-based algorithm being implemented by UC Berkeley. The algorithm detects Pm-waves at several times around an event epicenter and uses arrival times, amplitudes, and frequency content of the Pm-waves to rapidly estimate the magnitude and location of the event. ElarmS then uses regional GMPEs to predict the expected peak ground shaking throughout a region in real-time.

Figure 5: Map showing all ElarmS detected M>3.0 events, false and missed alerts during from 8 August through 20 October 2009. There were 55 M>3.0 events in Northern California during this testing period. ElarmS detected 45 events, missed 18 events, and sent 4 false alerts. ElarmS alert criteria is region-dependent, based on station density.

V. Virtual Seismologist (VS) Algorithm Highlights

The VS algorithm is a Bayesian network-based algorithm being implemented by the Swiss Seismological Service at ETH Zurich. The VS algorithm began real-time processing at the SCISN in July 2008. VS has also been installed more recently (Feb 2009) at BDSN and Merlo Park.

Figure 6 (left): VS real-time performance in Southern California from July 2008-Feb 2009. VS correctly detected 1970 M>3.0 events and 182 M>4.0 events during the first 6 months of testing. There are con-

Figure 7 (above): VS magnitude error as a function of nth VS estimate for M>3.0 events in ad-

Figure 8 (left): A screen shot of the CISN EEW Testing Center website showing the various types of summary reports being cre-

VII. Outlook and Conclusions

In August 2009, a second three-year study was initiated to integrate the three test algorithms into CISN ShakeAlert, a single prototype EEW system that will provide real-time warning information to a small group of test users by the end of the study in 2012.

Over the next 3 years, stimulus funding will be used to upgrade many of the older, slower dataloggers throughout the CISN. This will reduce the median station data latency from 5.2 seconds to 2.3 seconds.

The algorithm testing efforts clearly illustrate the benefits of dense station spacing to reduce false and missed alerts, as well as to im-

prove the speed of alert delivery. Enhancing the network to provide ~20 km inter-station spacing (as is found in Japan, San Francisco Bay Area, and Los Angeles) where EEW works relatively well throughout the source region of the San Andreas Fault system will require ~100 additional stations.

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