SHAKEALERT® EARTHQUAKE WARNING: THE CHALLENGE OF TRANSFORMING GROUND MOTION INTO PROTECTIVE ACTIONS

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Abstract

The USGS ShakeAlert® earthquake early warning (EEW) system is operational and providing public alerting in three West Coast states: California, Washington, and Oregon. Since 2006 the USGS has pursued a strategy of incrementally developing and rolling out EEW for increasingly larger areas and uses.As funding from federal and state budgets grew the system became more capable, detection methods were developed and improved, core network sensor stations were built or upgraded, and partners were enlisted to deliver alerts and implement protective actions. In the fall of 2018, the system became sufficiently functional to publicly declare it “open for business” in all three states for use by licensed partners to alert personnel in limited settings and take automated machine-to-machine actions. State-wide public alerting began in California in October of 2019, expanded to Oregon in March of 2021, and to Washington in May of 2021. Today millions of people can receive ShakeAlert-powered EEW through a variety of delivery methods and dozens of machine-to-machine protective systems are in place in transportation systems, utilities, fire stations, schools, hospitals, and public and private buildings. The ShakeAlert System implementation plan calls for a supporting network of 1,675 seismic stations. 1,129 (73%) have been completed and the rest should be done by 2025.

Introduction

Since 2006 the U.S. Geological Survey (USGS) along with partner organizations has beendeveloping the ShakeAlert Earthquake Early Warning (EEW) system for the highest risk areasof the United States: California, Oregon, and Washington. The purpose of the system is to reduce the impact of earthquakes and save livesand property by providing alert messages to the public via existing mass notification technologies and to institutional users and commercial service providers to trigger automated, user-specific protective actions.

The ShakeAlert System leverages the existing earthquake monitoring capability and expertise of the Advanced National Seismic System (ANSS)regional networks. The project is a collaboration ofmany organizations including the USGS, Caltech, UC Berkeley, the California Geological Survey,the California Governor’s Office of Emergency Services, the University of Washington, the University of Oregon, the University of Nevada, Reno, Central Washington University and UNAVCO. Dozens of public and private organizations and businesses are developing anddeploying ShakeAlert-powered products and services and ten organizations have received licenses to operate. The ShakeAlert System has been available to a limited number of beta users since 2012 but thefirst major rollout occurred in October 2018 when the system was declared “open for business” and made available to public and private institutional “pilot” users on the West Coast, including emergency responders, schools, utilities, rail systems, and businesses. Public mass alerting via authorized smartphone apps and Federal Emergency Management Agency's Wireless Emergency Alert (WEA) system began inCalifornia on October 19, 2019, expanded to Oregon on March 11, 2021, and to Washington on May 4, 2021. ShakeAlert-powered products andservices are now offered by 10 licensed operators who are part of a growing EEW industry.

Major System Components

The ShakeAlert system is made up of several major geographically distributed but tightly interconnected sub-systems and components. These are ground motion sensors networks, data processing and alert production centers, alert distribution systems, technical user implementations, a testing and performanceplatform, continuing research and development, and a robust education and outreach program.

Ground Motion Sensor Networks

The ShakeAlert build-out plan (Given et al., 2018) calls for a total of 1,675 high-quality, real- time seismic stations: 1,115 in California and 560in the Pacific Northwest. All sites have three- component strong motion accelerometers and about a quarter include broad-band seismometers. This number provides a typical station spacing of 10 km in urban areas, 20 km in seismic sourceareas that endanger population centers, and 40 km in other areas. About 1,229 seismic stations, 73%of the target number, are currently contributing data and the balance are being built with both federal and state funding. Early priority was given to covering the southern California, San Francisco Bay, and Seattle/Tacoma regions which are now at or near target density. Plans also call for using datafrom hundreds of existing high-rate, real-time GNSS receivers operated by USGS and cooperator networks.

The ShakeAlert System's public safety mission requires fast and reliable delivery of remote sensor data to processing centers. Resilience is aided by using many independent commercial and co-operator communication services (e.g., cellular, IP radio, microwave, satellite, and internet) as well as microwave and radio infrastructure operated by USGS, state agencies, and other partners.

Data Processing and Alert Centers

The ShakeAlert production system now inoperation (v2.1.5) is designed with both spatial andfunctional redundancy. Data processing centers aredistributed along the West Coast in Seattle, Washington, and Menlo Park, Berkeley, and Pasadena, California and are jointly staffed by USGS and university personnel. The system processing architecture has three major layers—a Data Layer for handling high volumes of real-time ground motion data; a Processing Layer that does waveform analysis, earthquake detection, magnitude calculation, and ground motion predictions, and finally an Alert Layer that decides when events should be published and creates various message products. System modules communicate using ActiveMQ message brokers.The Alert Layer meets U.S. government standards for data security and all high-level data are encrypted. All production servers and software components are continuously monitored using industry best-practices and standard tools to detect system faults, failures, security issues, and monitor state-of-health and resource usage. In addition, the system meets government requirements andstandards for its designation as a Highly Valued Asset by the Department of Homeland Securityand is subject to regular cybersecurity tests,reviews, and audits.

Scientific Algorithms

The system currently has two rapid earthquake detection algorithms. The first is EPIC which is based on the ElarmS algorithm (Chung et al., 2019).It creates short-term average/long-term average (STA/LTA) triggers in small, filtered time

windows and associates these into point-source solutions using a grid search method solutions and peak P-wave displacement to estimate magnitudes.EPIC has several checks to discriminate between random noise and earthquake shaking and includesa “filter bank” check to reject teleseisms. The second is FinDer (Finite-Fault Detector) which canproduce both a point-source or line-source solutionby estimating the fault’s centroid location, orientation, and length using a pattern search technique to fit ground motion observations to pre-calculated fault templates (Böse, et al., 2012). A Solution Aggregator combines EPIC and FinDer solutions into a single weighted average solution that is the basis for several alert and information products. The eqInfo2GM module (Thakoor et al., 2019) take this combined solution and uses ground motion prediction and intensity conversion equations to estimate the resulting distribution and value of instrumental Modified Mercalli Intensity (MMI), Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV). Finally, a Decision Module publishes the results to alert servers if theymeet the criteria for public release.

The system revises its solutions up to twice per second as the quake grows and more ground motion data become available. For large events,updates could continue for minutes.

Alert Products and Thresholds

To meet the needs of various users the ShakeAlert System produces three message product streams for each event, all of which are published as XML messages to a publish/subscribe system on USGS alert servers. Licensed users may subscribe to one or more of these message streams.The *dm_event* messages include the earthquake magnitude and location but no estimate of ground shaking. The *gm_contour* messages containmagnitude and location results plus contours (as 8- point polygons) of MMI shaking intensity. The *gm_map* messages include magnitude and location plus a 0.2°x0.2° (approximately 20km x 20km) map grid of the estimated MMI, PGA, and PGV distribution.

The ShakeAlert system can detect events as small as magnitude 2.5 in some areas and publishesevents of magnitude 3.5 or greater in order to exercise the system. Because its goal is to warn of potentially damaging shaking and frequent alerts could result in “alert fatigue”, distributers are bound in their license agreements to abide by public release thresholds based on magnitude and intensity. Public alerts delivered by the Federal Emergency Management Agency (FEMA) Wireless Emergency Alert System (FEMA, 2019) are sent only to the MMI 4+ area when the magnitude is 5.0 or larger. Apps are limited toalerting the MMI 3+ area when the magnitude is 4.5 or larger. Machine-to-machine applications may go down to magnitude 4.0.

Within a few minutes of each public alert, on- call personnel compare the ShakeAlert result to authoritative network solutions and initiate appropriate event follow-up messages and products.This includes a report for the USGS earthquake event pages summarizing how the ShakeAlert system performed.

Alert Distribution Systems

The USGS has the authority to generate alerts but does not have the infrastructure or budget for mass distribution. Public mass alerting depends on existing or newly developed mass alertingpathways. For example, FEMA's Integrated Public Alert and Warning System (IPAWS) distributes alerts to cellular mobile service providers who thenforward them to the public's smartphones and other devices as Wireless Emergency Alerts (WEAs). Limited speed tests indicate delivery performance is highly variable. Alerts may be received by some in as little as 4 seconds after an alert is published but delays of several to tens of seconds are more typical, and up to 25% of phones may never receive the alert at all.

Public alerts are also distributed by several partners using push notifications to smartphone apps. These include QuakeAlertUSA, MyShake, and Shake-ReadySD (San Diego). Google has integrated ShakeAlert messages with their Androidplatform reaching millions of people without the need to download an app. Another licensed operator, Global Security Systems, can deliver alerts encoded in commercial FM radio broadcasts to purpose-built devices and another pilot, Clover Alert, is doing the same over public televisionairwaves.

Technical User Implementations

Dozens of public and private partners aredeveloping ShakeAlert-powered products and services to take automated machine-to-machine actions. For example, San Francisco's Bay Area Rapid Transit (BART) System began slowing trains in August of 2012. Following their lead LA Metro, the Los Angeles area light rail system, and Metrolink, southern California's commuter rail system, began using ShakeAlert products in 2021. Two water controls companies, RH2 and Varius, market equipment to automatically control valves, gates, and pumps in municipal water, sewage, and power systems. Other licensed partners like Early Warning Labs, SkyAlert, and Valcom, provide systems to alert people or take automated actions inother venues like high-rise condos, fire stations,schools, hospitals, offices, and public buildings.

Testing and Performance Platform

The ShakeAlert System Testing andPerformance (STP) Platform provides quantitative assessment of the performance of individual algorithms and the system as a whole (Cochran, et al., 2018a). No change is made to the production systems' configuration or software without STP evaluation. The STP platform supports two testingmethodologies. Candidate changes are run in a live real-time environment that is identical to the actual production system for a minimum of two weeksbut usually longer. In offline testing, a suite ofhistorically recorded waveform sets is replayed in apseudo-real-time test environment. The test suite includes 65 Japanese events, 140 U.S. West Coast earthquakes, 63 regional and teleseismic events,and 36 sets of problematic signals like sensor re- centering and calibration events. Results for point source solutions are compared to the authoritative ANSS network solution and baseline runs. Also, ShakeAlert ground motion predictions are compared to ShakeMaps for each test event. If test results show an improvement in performance, the change is deployed. The effectiveness of testing is limited because there are few large U.S.earthquakes available for the test suite and many ofthe historic events that are available were recorded with older, sparser sensor networks than exist today. The STP Platform will evolve to accommodate new algorithms and other changes tothe system architecture. For example, new procedures and tools are being added to compare ground motion estimates rather than source results, like location and magnitude.

Continuing Research and Development

Research and development to improve thesystem is ongoing (Cochran et al., 2018b). Improvements are constantly being made to production algorithms to improve the speed and accuracy of source characterization and ground motion predictions.

New methods are under development. Test results of the PLUM (Propagation of Local Undamped Motion) algorithm (Cochran et al., 2019) suggest it could improve the performance of ShakeAlert and provide backup to more traditional methods, especially during complex sequences. Geodetic methods like GFAST-PGD (Williamson, et al., 2020) are also being developed and tested to improve alerts by better constraining the sourceextent and magnitude of large earthquakes.

Research into the theoretical limits to EEW and how to maximize its effectiveness is ongoing. Meier (2017) and Minson et al. (2018; 2019) have explored the limits of EEW and show that for shallow crustal earthquakes it is difficult to provideaccurate and timely warnings using high ground motion thresholds to initiate protective actions. Longer warning times are possible when lower ground motion thresholds are used but users will experience more cases where strong shaking does not arrive.

Social science research is also being done tounderstand human response to alerts and informdecisions about setting alert thresholds, alert messages, signals and sounds, effective public education, and appropriate protective actions. Currently 17 projects are under way at 10 universities and research institutions across 5 U.S. states, Canada, Europe, New Zealand, Japan, and Mexico.

Education and Outreach Program

For ShakeAlert products to be effective, people must be trained to react quickly and effectivelywhen they receive an alert. Also, institutional usersmust understand the system's benefits for their organization and be motivated to implement automated actions and provide announcements to their personnel. To accomplish this, the ShakeAlertproject includes a vigorous communications, education, and outreach effort with participationfrom stakeholders from all three states and Canada.

This effort is focused on five priorities: public preparedness, technical implementation, consistent messaging and communications, integration withother earthquake products, and development anddissemination of educational resources. A ShakeAlert Messaging Toolkit is available for free at (https://www.shakealert.org/messaging_toolkit/)that includes guidance, talking points, andmultimedia materials tailored to reach a variety of stakeholder groups. Materials are available in several languages and are intended to integrate with existing earthquake preparedness efforts, encourage consistent information about ShakeAlertSystem technology, and promote appropriate protective actions.

Conclusions

Although the ShakeAlert sensor network is not yet complete and the project is not fully funded, it is "open for business" and providing earthquake early warning for millions of Americans in the highest risk states of our nation: Washington, Oregon, and California. Automated machine-to- machine protective systems are installed in transportation systems, utilities, fire stations, schools, hospitals, and public and private buildings,and a budding EEW industry is growing. The system is transitioning from development to an operation and maintenance phase, but it will never be "finished". Much work remains to improve the reliability, speed, and utility of the alert messages and delivery to users. The public must be educated about the system's capabilities and limitations, and most importantly on how to protect themselves when they receive an alert. Decision makers need to be educated about the system's value in protecting their organization's people and infrastructure. Finally, the nascent EEW industry must be encouraged to flourish in order to maximize the benefits of EEW in reducing earthquake losses.

Disclaimer

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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