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ShakeAlert: A People-Focused Earthquake Early Warning System

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ABSTRACT

Approximately 143 million people in the United States live in areas of significant earthquake hazard, with one-third of the earthquake risk concentrated in California, Oregon, and Washington. The Federal Emergency Management Agency estimates that average annualized losses from earthquakes nationwide is ~$6.1 billion. In the next 30 years, California is very likely (99.7% chance) to have a M6.7+ earthquake, and the Pacific Northwest has a smaller (10%) chance for a M8-9 earthquake. Earthquakes of these sizes may cause considerable loss of life and property damage and earthquake early warning could help people respond to these earthquakes. The goal of earthquake early warning (EEW) is to provide alerts to people and automated systems to prompt protective actions before an area experiences shaking. The U.S. Geological Survey (USGS) manages the ShakeAlert® EEW System for the West Coast of the United States. ShakeAlert is a network of seismic sensors, high-speed computers, rapid communication pathways, geophysical data, and specialized software that work together to develop ShakeAlert-powered alerts. However, for ShakeAlert to be successful, operators must have a deep understanding of how various publics interact via this System. Here we demonstrate the successes of the ShakeAlert communication, education, outreach, and technical engagement program so far, with a look towards the future.

INTRODUCTION

The USGS with other state and federal partners developed the ShakeAlert System to improve public safety and reduce damage to property [8] Broadly, EEW systems work because seismic sensors quickly detect an earthquake once it begins using the primary seismic waves (P-waves) that precede the more damaging secondary waves (S-waves). In the United States, USGS operates the Advanced National Seismic System (ANSS) which, in conjunction with university and state partners, quickly detects earthquakes (Fig. 1). Next, the ground motion data from the earthquake is telemetered to a ShakeAlert Processing Center, where specialized software quickly estimates the location, magnitude, and shaking distribution of the earthquake. This information is published by the USGS as a "ShakeAlert Message," which is then made available to alert distribution partners. Alert distribution partners use this information to (a) develop and rapidly disseminate ShakeAlert-powered alerts via cell phones that warn people to take a protective action, such as "Drop, Cover, and Hold On"; or (b) trigger an automated system such as slowing a train, closing a valve to protect a water supply, or sending an announcement over a public address system (Fig. 1).

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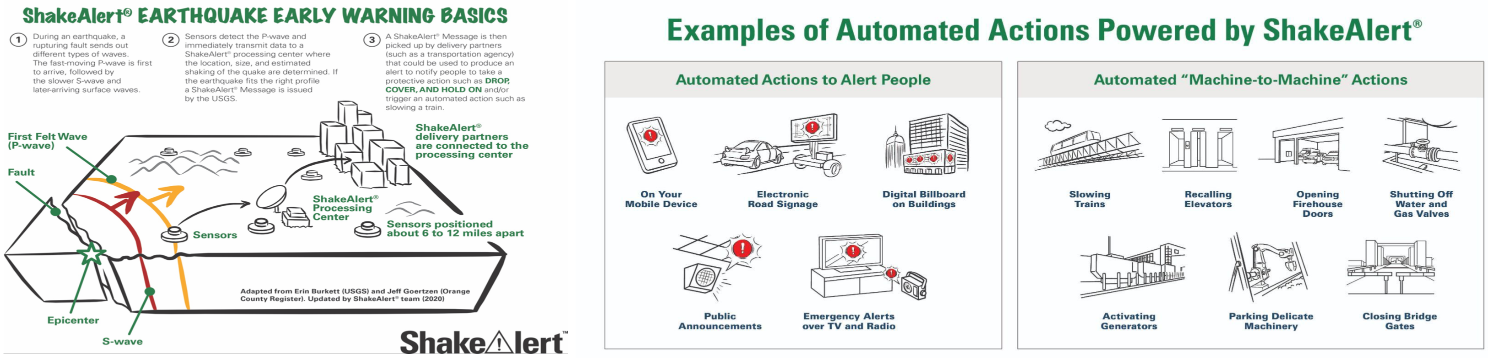

Figure 1: Graphics developed for the ShakeAlert Messaging Toolkit to illustrate and explain various aspects of the ShakeAlert System and how it operates. (Left) This illustration depicts how the system operates before ShakeAlert-powered alerts are delivered to people and technical systems. (near right) This graphic depicts various channels used to alert people, while (far right) this graphic illustrates automated "machine-to-machine" actions.

COMMUNICATION, EDUCATION, AND OUTREACH FOR SHAKEALERT

The successful implementation of an EEW system requires education, communication, and training on the system and its capabilities, as well as on what to do when an earthquake occurs, and a person receives an alert or experiences earthquake shaking. In 2016, the USGS formed the ShakeAlert Joint Committee for Communication, Education, Outreach, and Technical Engagement (JCCEO&TE). Over the last six years, the organizational structure of the JCCEO&TE has adapted and changed as different needs arise. The core personnel of the JCCEO&TE are social scientists, geoscientists, and education professionals at the USGS and other federal, local, and state governments, as well as at university and free-choice learning organizations in the three ShakeAlert states of California, Oregon, and Washington.

The initial working group of the JCCEO&TE was the Technical Users Working Group (TUWG). The aim of the TUWG is to inform and educate professionals within the burgeoning EEW industry about hazard and risk broadly so that they can be trusted sources of information among their colleagues and clients. Technical partners are public and private organizations who have a license agreement with the USGS to develop and bring to market products, services, and other applications that utilize the data contained in a ShakeAlert Message. A key criterion for alert delivery "License to Operate" is the ability of the technical partner to meet alert thresholds and delivery times to people and systems. ShakeAlert currently works with over 40 technical partners in sectors such as transportation, utilities, health care, education, and mass-notification education to deliver ShakeAlert-powered alerts to people and automated systems.

SOCIAL SCIENCE AND EDUCATIONAL RESEARCH FOR SHAKEALERT

A thorough understanding of how people interact with the ShakeAlert System is critical for operational success because actions by people and systems must be executed over a very short time duration. In 2018, the USGS acknowledged the need for a ShakeAlert-focused social science research program to identify barriers to understanding the content in EEW alerts, human behavior, and preferred protective actions. A preliminary analysis indicates that substantial barriers exist for populations with limited English language proficiency, literacy issues, and various access and functional needs, which account for roughly 40 percent of the population in the ShakeAlert states [1]. Previously, there was a dearth of literature about perceptions and attitudes around ShakeAlert, except for in Washington state [2]. To further explore these and other topics, and due to the lack of social science researchers at the USGS who specialize in natural hazards, ShakeAlert formed a group of academic researchers to conduct this work.

In March 2019, the Social Science Working Group (SSWG) met formally for the first time to explore various research questions related to ShakeAlert. The group meets virtually monthly and, in May 2021, held a research symposium that highlighted current and future research. A list of the 18 current and past projects coordinated by the SSWG is available in Supplement 1, Table 1. This list is not exhaustive and does not include the international work coordinated with New Zealand, Japan, Switzerland, Italy, and the United Kingdom. Research highlights include the development of post-alert messaging [1], warning message efficacy [3], protective actions guidelines [4], Wireless Emergency Alert latencies [5], generational differences around protective actions [6], ShakeAlert in museums [7] and how to build a more just and equitable EEW system [8].

To understand the current state of knowledge regarding earthquakes and EEW, the USGS held a series of four listening sessions from 2018-19 with local, state, and federal emergency managers, information technology professionals, teachers and instructors, parents, and other concerned community members in California, Oregon, and Washington. Based on these listening sessions, the USGS formed the Educational Resources Working Group (ERWG) to address earthquake-related misconceptions related to the basic physics of how earthquakes work, associated hazards and risk (to include tsunamis and volcanoes), and earthquake risk mitigation, which includes EEW. In collaboration with the Incorporated Research Institutions for Seismology (IRIS), the ERWG recognized that educational resources for ShakeAlert EEW needed to reach a variety of learning environments and learners who span a range of ages, expertise, and knowledge about earthquakes and EEW. Thus, the ERWG developed a novel approach that embeds adaptations to free-choice, informal, and formal learning environments and encourages multiple active learning modalities of hands-on participation, observation, and reflection through thinking questions as well as place-based data-oriented explorations.

In preparation for rollout of public alerting in the Pacific Northwest in spring 2021, the ERWG developed several animations in both English and Spanish to explain what actions to take in the event of an earthquake, how the ShakeAlert System works, and what information would be provided in a ShakeAlert-powered alert on a mobile device (Fig. 2). In particular, because the date of the Oregon rollout of public alerting was chosen to coincide with the ten-year anniversary of the 11 March 2011 M9.1 Great Japan earthquake, the ERWG developed an animation on the alert times people can expect during similar earthquakes in the Pacific Northwest based on a USGS Open-File Report [8]. When this animation was released in early July 2021, viewers watched it over 8,000 times within five days of release via YouTube, making it the most-viewed animation release in IRIS history. To understand what people learn from these animations about earthquakes, preparedness issues, and about ShakeAlert broadly, the ERWG, through the leadership of the Oregon Museum of Science and Industry, has initiated an evaluation of the ShakeAlert animation, “What is ShakeAlert”, which covers the basics of EEW for the West Coast of the United States.

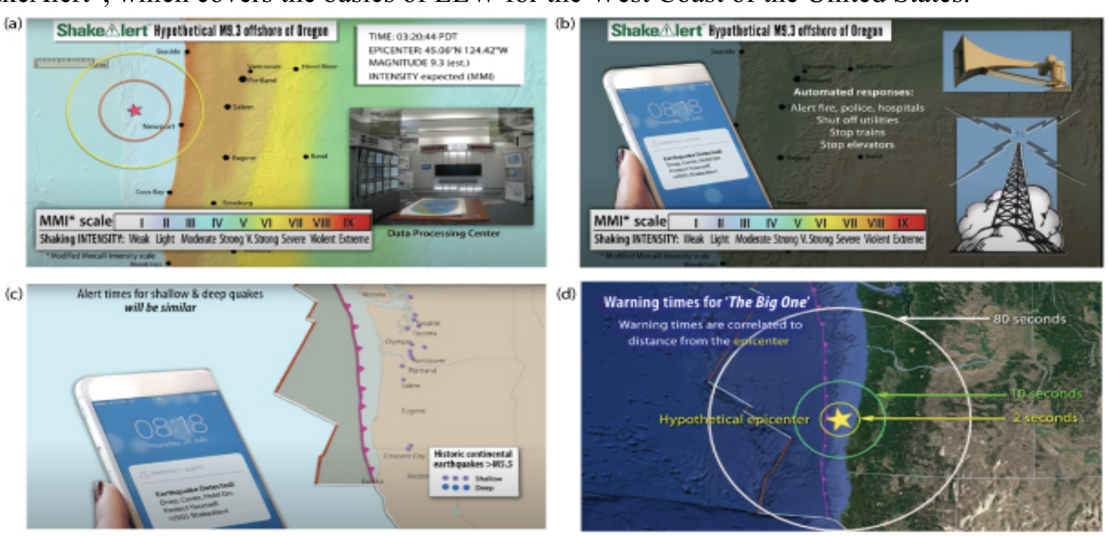

Figure 2: Screenshots from animations that describe how the ShakeAlert System works, including (a) a hypothetical M9.3 earthquake that occurs offshore Oregon and how ShakeAlert works to quickly detect an earthquake and determine its parameters, and (b) how ShakeAlert-powered alerts are received and trigger alert messages through various modalities and automated responses. Screenshots (c) and (d) are from the animation on alert times in the Pacific Northwest (PNW) based on the USGS Open-File Report [9] and show that (c) alert times for shallow and deep earthquakes in the PNW will be similar, while (d) warning times for 'The Big One' (a M8+ earthquake) will differ for communities, depending on how far they are from the epicenter.

CONCLUSIONS

ShakeAlert's success as a tool in everyone's earthquake risk-reduction toolbox depends on the resolve of the ShakeAlert community to make EEW accessible for all people. As with any human-centered, purpose-built system, technical EEW systems do not operate independently of societal systems that influence individuals' ability to receive and respond to alerts [10]. The ShakeAlert communication, education, outreach, and technical engagement (JCCEO&TE) team is charged with improving engagement approaches with various publics in the ShakeAlert states, where it is critical that ShakeAlert is integrated with other risk-reduction products and programs. For that reason, the JCCEO&TE team must understand and address the ways any of ShakeAlert's products, programs, or services could be biased (e.g., towards people with technological and sociocultural privilege), and take whatever steps necessary to truly make ShakeAlert an EEW System for all. After the rollout of public alerting in all three West Coast states was complete, work began on the 2021-26 JCCEO&TE strategic plan. In this plan, there is a focus on strategies to expand the buildout of the EEW industry, which is critical to offering as many ways as possible for people to receive ShakeAlert-powered alerts. There is also a focus on working with the ShakeAlert states to implement long-term inclusive and sustainable Communication, Education, Outreach, and Technical Engagement programming. For example, the plan will incorporate dynamic and tailored approaches specifically for people with disabilities, access, and functional needs.

ShakeAlert's place in the broader world of earthquake preparedness and information products merits consideration. EEW is not meant to substitute for any existing preparedness procedures, such as retrofitting unreinforced masonry structures or developing preparedness plans. The ShakeAlert CEO&TE program's resources are intended to enhance and align with other earthquake CEO initiatives, such as the Earthquake Country Alliance and their Seven Steps to Earthquake Safety program [4]. ShakeAlert complements the other ANSS information products and tools. There are ANSS products that are available before an earthquake and just after it begins (i.e. ShakeAlert), as well as a vast array of post-earthquake products available minutes to days afterward. The full suite of USGS products helps inform physical and social scientists, educators, and stakeholders about earthquakes to help better plan and prepare for the future. ShakeAlert is a system of hardware and software within a broader System that includes delivery mechanisms, messaging, and, most importantly, people. ShakeAlert will undoubtedly enhance its ability to reduce risk from earthquakes risk if this holistic and inclusive approach is part of the ShakeAlert System and incorporated into future developments of EEW.

Acknowledgments

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. We thank our internal U.S. Geological Survey reviewers, Valerie Thomas, Jessie Saunders, and Suzanne Hecker for their thoughtful feedback which improved this article.

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Supplement 1

Table 1: Social Science Working Group Research projects

Title of Project	**Researchers**	**Publications and Research in Progress**
ShakeAlert Post-Alert Messaging	McBride (Lead), Bostrom, Sutton et al.	McBride, S. K., Bostrom, A., Sutton, J., de Groot, R. M., Baltay, A. S., Terbush, B., Bodin, P., Dixon, M, Holland, E., Arba, R., Laustsen, P., Liu, S. Vinci, M. (2020). Developing post-alert messaging for ShakeAlert, the earthquake early warning system for the West Coast of the United States of America. International Journal of Disaster Risk Reduction, 50, 101713.
Diversity, Equity, and Inclusion for ShakeAlert	Jenkins (Lead), McBride, Morgoch, Smith	Jenkins, M.R., McBride, S.K., Morgoch, M. and Smith, H. (2022), "Considerations for creating equitable and inclusive communication campaigns associated with ShakeAlert, the earthquake early warning system for the West Coast of the USA", Disaster Prevention and Management, Vol. 31 No. 1, pp. 79-91. https://doi.org/10.1108/DPM-03-2021-0090
Ridgecrest Earthquake Sequence Research: Public Responses to the 2019 Ridgecrest Earthquake Sequence and ShakeAlert	Sutton (Lead), Wood, Waugh	Project including focus groups and interviews of residents who received a false alert in 2020.
ShakeAlert Message Testing and Video Education.	Sutton (Lead)	Sutton, J., Fischer, L., James, L. E., & Sheff, S. E. (2020). Earthquake early warning message testing: visual attention, behavioral responses, and message perceptions. International journal of disaster risk reduction, 49, 101664.
ShakeAlert's Community of Practice: Qualitative and Collaborative Research on ShakeAlert Operations With USGS	Reddy (Lead), McBride, de Groot	Ethnographic study of the ShakeAlert system.
ShakeAlert in Schools	Peek (Lead), Adams, Tobin, Breelan, de Groot, McBride	Adams, R., Tobin, J., Peek, L., Breeden, J., McBride, S.K., deGroot, R.M. (2022, in press).The Generational Gap: Children, Adults, and Protective Actions in Response to Earthquakes. Australasian Journal of Disaster and Trauma Studies

Inclusive Messaging for ShakeAlert	Morgoch (Lead), Smith, McBride, de Groot	Quantitative research regarding perceptions and attitudes of ShakeAlert in Oregon.
CCTV Analysis Project	Baldwin (Lead), Gin, Bellizzi, Mendez, Santos-Hernandez, McBride, Sumy	Video analysis of human behavior during earthquakes.
Cross-Platform Analysis of Public Responses to the 2019 Ridgecrest Earthquake Sequence on Twitter and Reddit.	Ruan (Lead), Kong, McBride, Sethjjwala, Lv.	Ruan, T., Kong, Q., McBride, S. K., Sethjiwala, A., & Lv, Q. (2022). Cross-platform analysis of public responses to the 2019 Ridgecrest earthquake sequence on Twitter and Reddit. *Scientific Reports, 12*(1), 1634. doi:10.1038/s41598-022-05359-9.
Wireless Emergency Alert Testing	McBride, (Lead), Sumy, Llenos, McGuire et al.	Article describing latency testing for Wireless Emergency Alerts.
ShakeAlert In Museums	Sumy (Lead), Jenkins, de Groot, McBride	Sumy, D. F., Jenkins, M. R., McBride, S. K., & de Groot, R. M. (2022). Typology development of earthquake displays in free-choice learning environments, to inform earthquake early warning education in the United States. *International Journal of Disaster Risk Reduction*, *73*, 102802.
Adding ShakeAlert Questions to Did You Feel It?	Goltz (Lead), Wald, McBride, de Groot	Research includes article outlining process of developing survey questions to add to DYFI.
Computer Simulations for Optimal Protective Actions	Zhao, Cova, Wood, Baldwin, Luco, McBride	Wood, M., Zhang, X., Zhao, X., McBride, S.K., Luco, N., Baldwin., D. Cova, T. (2022, in press). Earthquake Early Warning: Toward Modeling Optimal Protective Actions. Conference paper for NCEE12, June 30 – July 3, 2022, Salt Lake City, Utah.
Disability Studies to Improve Technological and Protective Actions	Farmer (Lead PI), Tran, Sumy, Jenkins, McBride, de Groot	Review article in process for considerations of disabilities, accessible technologies, and EEW.
ShakeAlert and Protective Actions	McBride, Smith, et al.,	McBride, S. K., Smith, H., Morgoch, M., Sumy, D., Jenkins, M., Peek, L., Bostrom, A., Baldwin, D., Reddy, E., de Groot., R.M., Becker, J., Johnston, D.M.,Wood, M. (2021). Evidence-based guidelines for protective actions and earthquake early warning systems. Geophysics, 87(1), 1-79.

Media Analysis of ShakeAlert Rollouts	Smith and McBride	Media analysis of the three state (Oregon, California, and Washington) of the ShakeAlert rollouts.
Tsunami and Earthquake Early Warnings	McBride and Sumy	Sumy, D. F., McBride, S. K., von Hillebrandt-Andrade, C., Kohler, M. D., Orcutt, J., Kodaira, S., ... & Collins, J. (2021). Long-term ocean observing coupled with community engagement improves tsunami early warning. *Oceanography*, *34*(4), 70-77.
ShakeAlert Perceptions, Attitudes, Knowledge, and Expectations Study	Bostrom (Lead PI), McBride, de Groot, Goltz, Peek	Article regarding survey results about perceptions, attitudes, and knowledge of ShakeAlert and EEW systems.

J. Lord[1] and R. Wright[2]

ABSTRACT

This template illustrates the format that must be used in the preparation of papers for the Twelfth U.S. National Conference on Earthquake Engineering. Text and headings should be in 12-point type. Included in this template are examples of headings, equation format, references, and other typographical features likely to be encountered in technical papers. **Maximum paper length is 4 pages for a full paper.** A good abstract should be an informative summary of the most important results. It should not be a summary of subjects covered. It should avoid expressions such as "is discussed" and "is described." It should not include references, figures, or tables. The abstract is of utmost importance, because it is the most widely read portion of a manuscript. Abstracts should be no more than 200 words.

Introduction

The proceedings of the conference will be compiled directly from the documents received from authors. Therefore, to enhance the overall visual quality of the proceedings, each author should make every effort to comply with the guidelines in the document entitled "12NCEE Paper Formatting Instructions." The purpose of this template is to aid in clarifying those guidelines.

Author Affiliations

The authors' institutional affiliations and addresses are to be given in single-line form at the bottom of the first page. The last affiliation line should rest on top of an empty line that separates the last author affiliation and the bibliographical reference of the paper. The topmost affiliation line should be directly beneath a two-inch rule. The line should an email address contacting the author. Example illustrates format.

Bibliographical Reference of the Paper

A bibliographical reference of the paper should be included in the footer of the paper. One line should separate the last author affiliation and the bibliographical reference of the paper. The last line of the bibliographical reference should rest on the bottom margin of the page.

Margins

Both justified and ragged right margins are acceptable. However, as some word processors justify right margins

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with awkward character and word spacing, authors should exercise their judgment and select the option that provides the best presentation for their papers.

Heading 1 Example

The styles for three levels of headings are specified. Heading 1 is shown at the beginning of this section.

Headings should be preceded by a one-line space. Do not indent the first line of the first paragraph. Use 0.5 inches of indentation on the first line of the following paragraphs.

Heading 2 Example

Heading 3 Example

Special Features

Among the special features likely to be encountered in a technical paper are equations, figures, tables, and references. This section will show how to deal with these features.

Equations

Equations should be indented 0.5 inch from the left margin, should have a reference number in parentheses flush with the right margin, and should be preceded and followed by a one-line space. For example,

$$[M]\{\ddot{U}\} + [K]\{U\} = \{f(t)\} \tag{1}$$

where [M], [K], $\{\ddot{U}\}$, and {U} are variables in the equation and should be described in the text. Awkward line spacing caused by in-line equations should be avoided. Equations should be referred to in the text as Eq. 1, or as Eq. 2, 3, and 4.

Figures and Tables

Figure 1. A figure in the text; first letter capitalized, period at end, and indent following lines as shown. If the

caption is short, authors should center it under the figure.

As possible, Figures and tables should be included in the body of the text directly after cited. Placement of tables and figures in the text where reference is made to them is encouraged, as it enhances readability. Each figure should be referred to by number in the text, as in Fig. 3, or as in Figs. 3, 4, and 5. Similarly, tables should be referred to as Table 3, or Tables 3, 4, and 5. All figures and tables **must** be referred to and described in the text. Figure captions should be placed below the figure and table captions above the table. Leave at least a one-line space between text and captions.

Table 1. Captions of tables; indent following lines with period at end. If the caption is short, authors should center it above the table.

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References Within Text

References should appear together in the References section (see below) and be listed by number within square brackets in the order in which they appear in the text. All references **must** be cited in the text with numbers inside brackets [1].

Conclusions

Each paper is expected to concisely state the conclusions of the work. The Conclusions section should discuss the significance and applicability of the work, and not merely restate the abstract. Great care should be exercised to make explicit the limitations or conditions under which the results can be applied.

Acknowledgments

Acknowledgments should be succinct and used only as necessary.

Appendix

Appendices only should be used to provide information that would otherwise interrupt the principle focus of the paper or to provide supplemental information to be read by a small portion of the readership. If more than one appendix is necessary, they should be numbered. Appendices should precede the References section. Once complete, save this document as a PDF using the most recent version of Adobe, check PDF file for appropriate formatting and upload to the submission site.

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