P. Gasparini · G. Manfredi · J. Zschau (Eds.)

Earthquake Early Warning Systems

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Paolo Gasparini
Gaetano Manfredi
Jochen Zschau

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With 153 Figures

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PROF. PAOLO GASPARINI
University of Napoli
Department of Physics
Via Cintia
80126 Napoli
Italy
E-Mail: paolo.gasparini@na.infn.it

PROF. GAETANO MANFREDI
University of Napoli
Department of Structural Engineering
Via Claudio 21
80125 Napoli
Italy
E-Mail: gaetano.manfredi@unina.it

PROF. DR. JOCHEN ZSCHAU
GeoForschungsZentrum Potsdam
Telegrafenberg E 425
14473 Potsdam
Germany
E-Mail: zschau@gfz-potsdam.de

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Preface

In the last few decades economic losses due to natural disasters have increased exponentially worldwide and little progress has been seen in reducing their rate of fatalities. This also holds for earthquake disasters and is mainly due to increasing population and industrial density in high hazard and vulnerability areas. Although the prediction of earthquakes is not yet practicable, current technology allows prompt identification of the onset of any dangerous seismic event. Hence *early warning and rapid disaster information systems* are becoming important means for strengthening prevention and social resilience against the adverse effects of major natural events and should therefore become the keystones of disaster mitigation. The term *early warning* is now widely used with various meanings in scientific, economic and sociological communities. Even in the scientific world the term is used in slightly different ways although there is a growing consensus in defining *early warning* as all the action that can be taken during the *lead time* of a catastrophic event. The *lead time* is defined as the time elapsing between the moment when the occurrence of a catastrophic event in a given place is reasonably certain and the moment it actually occurs. Typical lead times are of the orders of seconds to tens of seconds for earthquakes, minutes to hours for tsunamis, and hours to days for landslides, floods and volcanic eruptions.

In more general terms, early warning is the provision of timely and effective information, through identified institutions, allowing individuals exposed to a hazard to take action in order to avoid or reduce their risk and prepare for effective response.

Although the definition of lead time for non-seismic hazards may be ambiguous (the term "reasonably certain" may need a more precise probabilistic definition), for earthquakes the definition is unequivocal as the lead time will start when the first waves are released by the earthquake source. Indeed, the physical basis for earthquake early warning is simple: strong ground shaking is caused by shear-waves and by the subsequent surface waves which travel at about half the speed of the primary waves and much slower than electromagnetic signals transmitted wireless and/or by cable. Thus, depending on the distance of a strong earthquake from the endangered urban area, transmission of information and real-time analysis of the fast primary wave may provide warnings from a few seconds to a few tens of seconds before the arrival of strong ground shaking. This may be used to minimize property damage and loss of life in urban areas and to aid emergency response. When a suitable seismic network is available fast processing methods can be applied to locate an earthquake, determine the magnitude, and estimate the distribution of ground motion (regional approach). At a site or structure equipped with seismic sensors, a site-specific warning is possible using the first low amplitude arrivals (P-waves) to infer the motion due to the following high amplitude shear and superficial waves (on-site approach).

The application of earthquake early warning systems (EEWS) can be very effective in real time risk mitigation, enhancing the safety margin of specific critical engineered systems such as nuclear power plants, lifelines or transportation infrastructures by reducing the exposure of the facility with automated safety actions. The early warning system can be used to trigger the orderly shutdown of pipelines and gas lines to avoid fires, or the shutdown of manufacturing operations to reduce both potential damage to equipment and industrial accidents. Also, personal safety might be enhanced if people were alerted. In addition, the functions of modern society will be less likely to turn chaotic if an early earthquake alert is available and if training of appropriate actions has been performed. Last not least, emergency response teams may be dispatched where they are needed most if maps of strong ground shaking can be provided by the early warning system within a few minutes.

In addition, seismic early warning systems can be of great value in reducing damage and loss due to secondary events triggered by earthquakes. These may include landslides, tsunamis, fires and industrial accidents. The fires that devastated San Francisco after the 1906 earthquake and the tsunami of December 2004 in Indonesia are two classic cases, but in most of the major earthquakes economic losses and human casualties have been enhanced by secondary phenomena.

Despite the above considerations, at present the potential of seismic early warning methods is not fully used. This is not only true for developing countries but also for highly industrialized countries including those of Europe.

Most existing seismological processing methods have not been developed or optimized for real-time or near real-time applications as required for early warning. The development of real-time analysis, modeling and simulation methods, their integration with appropriate facilities for data processing, visualization and rapid information systems and their application to earthquake early warning in conjunction with disaster management is, therefore, one of the major challenges of today's seismology.

All of these issues were raised and discussed during a workshop held in Naples, Italy, on September 23-25 2004, focusing on "Seismic Early Warning for European Cities: toward a coordinated effort to raise the level of basic knowledge". The workshop was organized in the framework of the EC FP 6 SSA Project "Natural Risk Assessment (NaRAs)". Researchers attending the meeting from eight European countries (France, Germany, Greece, Iceland, Italy, Portugal, Switzerland, Turkey), United States, Japan and Taiwan unanimously approved a recommendation submitted to the European Commission, stressing the still unresolved basic questions for full application of earthquake early warning to society's needs and asking for future calls to contain specific reference to seismic early warning methods.

This book is mostly based on the articles that were presented at the workshop. Given the long time needed to collect all of them, they have since been updated. They were written in their final form at the end of 2006.

The short review by Hiroo Kanamori points out the main problems for automatic application of earthquake early warning to real time risk reduction.

One of the basic problems in seismic early warning is the development of real-time algorithms for fast determination of earthquake source parameters and the estimation of their reliability. This includes the problems of real-time event detection and location, real-time fault mapping as well as new approaches for fast magnitude/moment determinations based on strong motion data, modern seismic array technology and the concept of energy magnitude. The latter promises to be extremely useful for estimating the size of mega-events. The scientific and technological challenge is to obtain this kind of information only a few seconds after the first P-wave arrivals. Classic seismic processing tools still need larger portions of a seismogram and are thus not suited to this purpose.

A group of five papers deals with the above problems. In particular, the paper by Stefan Nielsen discusses from a theoretical viewpoint whether reliable information on the size of an earthquake can be obtained from processing the waves released at the onset of a fracture. The paper by Richard Allen discusses the ElarmS system based on the processing of first P-wave arrivals to predict ground motion at different sites. Aldo Zollo and Maria Lancieri use an earthquake database to simulate real-time magnitude determination from the Earthquake Early warning system implemented in the Campania Apennines. They identify the parameters most robustly correlated with moment magnitude. Maren Böse et al. present the PreSEIS (pre-seismic shaking) method they developed and applied to the Istanbul case. The method is based on an artificial neural network and is as fast as the on-site warning approach, because it combines information from several sensors within small seismic subnets with apertures of about one hundred kilometers to estimate source parameters from the first few seconds of seismic recordings. Satriano et al. present an evolutionary method for real-time location based on the equal differential time formulation and a probabilistic approach.

Along with the development of appropriate real-time algorithms, it is crucial to develop a strategy for rapidly communicating the obtained seismic information not only to the disaster managers, but also to other interested parties from civil protection, politics, media, science and the public. The warning time involved in this task may, however, have to be extended to minutes, tens of minutes or more. Of special importance for emergency planners will be the concept of the virtual seismologist, which takes into account pre-existing information to estimate and possibly reduce the uncertainties of source parameter determinations, and which, in particular, can deduce from the source parameter information specific decision support for disaster management, as discussed in the paper by Georgia Cua and Thomas Heaton.

The evolutionary method and the virtual seismologist concept are very useful for providing continuously upgraded real-time alert maps and predicted shake maps within seconds and minutes as well as maps of measured ground shaking within a few minutes after the event. The development of proper attenuation algorithms, as discussed by Vincenzo Convertito et al., is crucial in order to also account for site corrections in such maps. Maps of expected ground motion before a catastrophic event for various scenarios are useful information to design the way effects of ground vibrations on structures can be reduced as well as for fast map calibration once the event occurs. 3D simulations of ground response and the key parameters needed to optimize the probabilistic approach are discussed by Jean Virieux et al.

Earthquake Early Warning Systems are efficient tools in urban areas where a significant portion of the buildings are structurally deficient. In cases where the seismic source zone is clearly known and sufficiently far away, the population can be warned by radio, television, etc. Operation of critical facilities and processes can be stopped. In the case of very short pre-warning times of a few seconds, it is still possible to slow down trains, to switch traffic lights to red, to close valves in gas and oil pipelines, to release a SCRAM in nuclear power plants, etc. Early warning systems can also be used to alarm the population where rapid response is needed. A typical example would be to issue the so-called water alarm, i.e. alarming the population living in the downstream region of a large dam. Early warning systems are useful for facilities and processes, such as nuclear power plants, high speed trains, gas mains and highways, where rapid response can contribute to reduction in the seismic risk.

In addition to such immediate uses, further development of an early warning system may include the implementation of semi-active interfaces with infrastructures that can use the early warning information for real-time risk reduction. For example, construction companies in Japan are developing buildings with semi-active control systems. The buildings can change their mechanical properties within a few seconds to better withstand ground motion. Implementation of this "few seconds engineering" requires careful assessment of the false alarms or "cry wolf" and missed alarm probabilities on the decision chain as discussed in the papers by Grasso et al., and Iervolino et al. A second paper by Iervolino et al. discusses several real-time engineering applications in the light of performance-based earthquake engineering for risk reduction.

Finally in the last part of the volume four different earthquake early warning systems are described, which are already in operation.

The first system to be operative in the world was the UrEDAS (Urgent Earthquake Detection and Alarm System). It was implemented to protect sections of the fast Japanese Railway Systems. The history of seismic early warning since the original idea of J.F. Cooper in 1868, the development of the UrEDAS system and a report of its performance are given by Nakamura and Saita. The same authors also describe a portable device for on-site early warning applications.

The early warning system implemented in Taiwan, described in the article by Wu, is a regional system which can issue an alert after 22 sec from the onset of an event. This gives a lead time of more than 10 sec to locations more than 100 km away from the epicentre, and the application of a novel processing method has the perspective of decreasing the processing time to about 10 sec and the "blind" zone to about 25 km.

The system implemented in Romania was designed to protect mainly Bucharest and some industrial structures from the intermediate depth earthquakes originating in the Vrancea region. Some specific characteristics of the seismic activity (such as the stationary epicentres, the stability of radiation patterns) and a line-of-sight connection between the epicentral area and the capital allowed a simple and robust system to be designed, which is currently being tested to protect a nuclear power plant, as described by Marmureanu et al.

The fourth system, described by Weber et al., is being implemented in the Campanian Apennines, southern Italy, along the fault systems which have been the source of many strong crustal earthquakes in previous centuries (the last occurred in 1980). It is a local network broadcasting the signals to the city of Naples, developed together with the Civil Protection of the Campania Regional Authority.

The systems described in this book do not cover all the existing operational systems. For the sake of completeness, at least two further cases are mentioned in the paper by Iunio Iervolino, Gaetano Manfredi and Edoardo Cosenza in their review of engineering applications, namely the regional system implemented to protect Mexico City and the local system designed for the Ignalina nuclear power plant in Lithuania.

The seismic alert system (SAS) for Mexico City (Mexico) is an EEWS for large earthquakes, which are likely to cause damage in Mexico City and have their source in the subduction zone of the Pacific coast at a distance of about 320 km. The warning time varies between 58 to 74 seconds. Information received from the stations is processed automatically to determine magnitude and is used in the decision to issue a public alert. The Radio Warning System for users disseminates the seismic early audio warnings via commercial radio stations and audio alerting mechanisms to residents of Mexico City, public schools, government agencies with emergency response functions, key utilities, public transit agencies and some industries. During rush hours, approximately 4.4 million people are covered by the system.

The seismic alarm system for the Ignalina nuclear power plant in Lithuania consists of a Seismic Alarm System (SAS) designed to detect potentially damaging earthquakes and to provide an alarm before the arrival of the shear waves at the reactor. Six SAS stations are installed at a distance of 30 km from the power plant forming an array, which is referred to as a seismic "fence". An earthquake with an epicenter outside the fence is detected about 4 seconds before it is "felt" by the reactor. The required time to insert the control rods is 2 seconds. Potentially, the reactor could be shut down before the earthquake arrives. At present, the SAS will only initiate an alarm signal.

A few recent examples of practical use of earthquake early warning information are shortly discussed in the review paper by Kanamori.

We hope that the contents of this book show convincingly that implementation of effective earthquake early warning systems is scientifically and technologically feasible. However, to be really effective any early warning system must include three components:

1. the scientific-technological component that provides information on an impending extreme event,
2. the decision making component that issues a warning, and
3. the response component that ensures an adequate response to the warning.

Today, the main problems in this warning chain occur as a result of inadequate interaction between these different components. This is particularly true for earthquake early warning. Even when the technological means necessary for earthquake early warning, such as seismic instrumentation, computerized systems and telecommunication, are in place, their ability to serve the needs of disaster management and decision makers has only been marginally exploited.

We have the feeling, shared by most of the scientific community, that "end users", such as civil defense organizations, industries and public administrators, react very cautiously to the challenge issued by the scientific community due to the complexity they foresee in activating the second and third components of the earthquake early warning chain. Indeed, sound information and education of the public and officials living in the "protected" area are required in order to produce an effective increase in resilience.

In turn, close interaction between scientists, administrators and the public is the path to follow to take full advantage of the developments offered by science and technology to allow people to continue to live in areas prone to natural hazards with an acceptable level of risk.

Paolo Gasparini
Gaetano Manfredi
Jochen Zschau

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Contents

List of Contributors

Richard M. Allen
Seismological Laboratory, Department of Earth & Planetary Science, University of California Berkeley, CA, USA

Pierre-Yves Bard
LGIT – Maison des Géosciences, Saint-Martin-d'Hères, France

James L. Beck
Department of Applied Mechanics and Civil Engineering, Caltech

Antonella Bobbio
Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Napoli, Italy

Maren Böse
Karlsruhe University, Geophysical Institute, Karlsruhe, Germany

Luciana Cantore
Dipartimento di Scienze Fisiche, Università di Napoli Federico II, Napoli, Italy

Vincenzo Convertito
Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Napoli, Italy

Margherita Corciulo
Dipartimento di Scienze Fisiche, Università di Napoli Federico II, Napoli, Italy

Edoardo Cosenza
Dipartimento di Ingegneria Strutturale, Università di Napoli Federico II, Napoli, Italy

Georgia Cua
Swiss Seismological Service, Swiss Federal Institute of Technology (ETH) Zurich, Switzerland

Raffaella De Matteis
Dipartimento di Studi Geologici ed Ambientali, Università degli Studi del Sannio, Benevento, Italy

Martino Di Crosta
Dipartimento di Scienze Fisiche, Università di Napoli Federico II, Napoli, Italy

Luca Elia
Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Napoli, Italy

Antonio Emolo
Dipartimento di Scienze Fisiche, Università di Napoli Federico II, Napoli, Italy

Mustafa Erdik
Bogazici University, Kandilli Observatory, Istanbul, Turkey

Massimiliano Giorgio
Dipartimento di Ingegneria Aerospaziale e Meccanica, Seconda Università di Napoli, Aversa, Italy

Veronica F. Grasso
Dipartimento di Ingegneria Strutturale, Università di Napoli Federico II, Napoli, Italy; Visiting Special Student, Caltech

Adrian Grigore
National Institute for Earth Physics, Bucharest, Romania

Thomas Heaton
Department of Civil Engineering, California Institute of Technology, Pasadena, USA

Nai-Chi Hsiao
Central Weather Bureau, Taipei, Taiwan

Giovanni Iannaccone
Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Napoli, Italy

Iunio Iervolino
Dipartimento di Ingegneria Strutturale, Università di Napoli Federico II, Napoli, Italy

Constantin Ionescu
National Institute for Earth Physics, Bucharest, Romania

Hiroo Kanamori
Seismological Laboratory, California Institute of Technology Pasadena, CA, USA

Maria Lancieri
RISSC-Lab, Dipartimento di Scienze Fisiche, Università di Napoli Federico II, Napoli, Italy

William H.K. Lee
U. S. Geological Survey (retired), Menlo Park, CA, USA

Anthony Lomax
Anthony Lomax Scientific Software, Mouans-Sartoux, France

Gaetano Manfredi
Dipartimento di Ingegneria Strutturale, Università di Napoli Federico II, Napoli, Italy

Alexandru Marmureanu
National Institute for Earth Physics, Bucharest, Romania

Gheorghe Marmureanu
National Institute for Earth Physics, Bucharest, Romania

Claudio Martino
Dipartimento di Scienze Fisiche, Università di Napoli Federico II, Napoli, Italy

Hormoz Modaressi
BRGM, ARN, Orléans, France

Yutaka Nakamura
System and Data Research Co. Ltd.

Stefan Nielsen
Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy

Annalisa Romeo
Dipartimento di Scienze Fisiche, Università degli Studi di Napoli Federico II, Napoli, Italy

Jun Saita
System and Data Research Co. Ltd.

Claudio Satriano
RISSC-Lab, Dipartimento di Scienze Fisiche, Università di Napoli Federico II, Napoli, Italy

Tzay-Chyn Shin
Central Weather Bureau, Taipei, Taiwan

Ta-liang Teng
Southern California Earthquake Center, University of Southern CA, Los Angeles, CA, USA

Jean Virieux
Géosciences Azur, Valbonne, France

Emanuel Weber
Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Napoli, Italy

Friedemann Wenzel
Karlsruhe University, Geophysical Institute, Karlsruhe, Germany

Yih-Min Wu
Department of Geosciences, National Taiwan University, Taipei, Taiwan

Aldo Zollo
RISSC-Lab, Dipartimento di Scienze Fisiche, Università di Napoli Federico II, Napoli, Italy

1 Real-time Earthquake Damage Mitigation Measures

Hiroo Kanamori

Seismological Laboratory, California Institute of Technology Pasadena, CA, USA

Abstract

Some reflections on real-time earthquake information and early warning methods application to risk mitigation are discussed. A list of application and the recent obtained results are discussed. The main seismological problems related to the implementation of the method are outlined.

1.1 Introduction

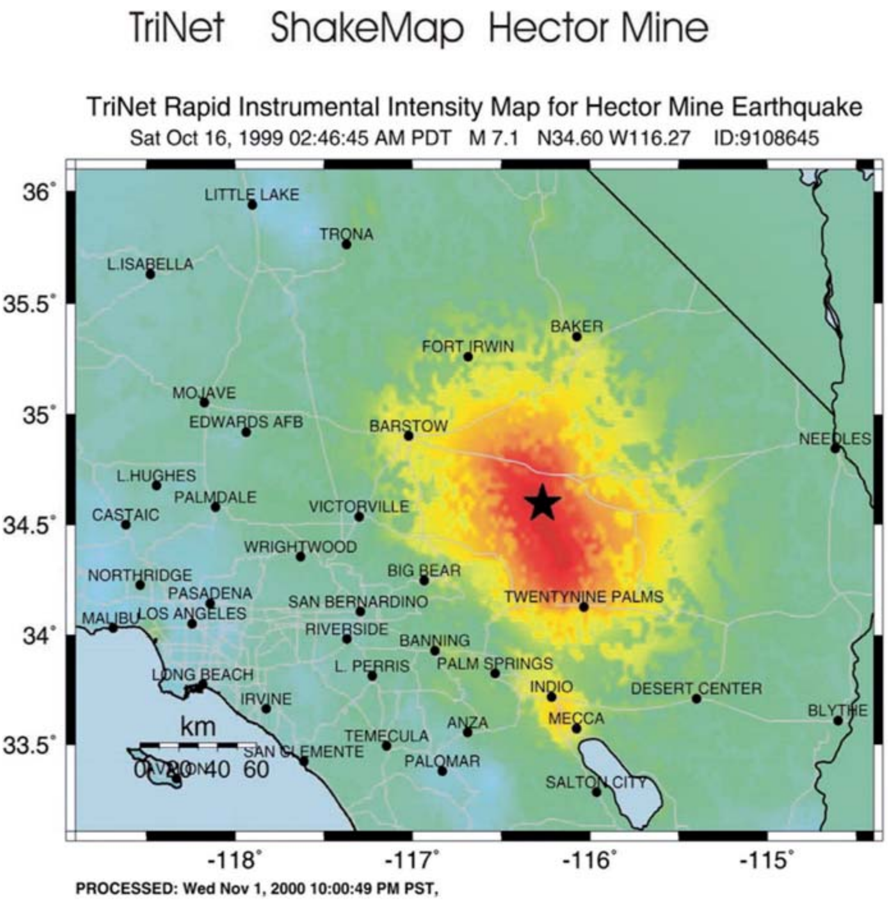
Real-time earthquake damage mitigation refers to a practice with which we rapidly determine immediately after a significant earthquake the source parameters and the estimated distribution of shaking intensity and distribute the information to various users. The users include emergency services officials, utility companies (electric, water, gas, telephone etc), transportation services, media, and the public. This information will be useful for reducing the impact of a damaging earthquake on our society.

In most cases, it takes a few minutes to hours to process the data and when the information reaches the users, the damage may have already occurred at the user site. In this case, the information is called the post earthquake information. This information is important for orderly recovery operations in the damaged areas.

In contrast, if the data processing and information transfer can be done very rapidly (i.e., within 10 sec), the information reaches some sites before shaking starts there. In this case, the information is called “Earthquake Early Warning” (EEW). This concept has been around for more than 100 years, but it had not been put in practice until recently for technical and practical difficulties. In Japan, in conjunction with the operation of the high-speed bullet train (Shinkansen) in the 1960s, a warning system for impending ground shaking after a nearby large earthquake was implemented. This system was later extended to UrEDAS (Nakamura 1988, Nakamura and Saita 2007, this issue) which led the subsequent developments for earthquake early warning methodology for more general purposes.

1.2 Post-Earthquake-Information and Earthquake Early Warning

Post earthquake information was routinely issued by various organizations such as the U.S. Geological Survey (USGS) and the Japan Meteorological Agency (JMA), and has been widely used. In California, a project to distribute post earthquake information to various users began in the 1990s. This project was called CUBE (Caltech-USGS Broadcast of Earthquakes) and aims at not only just distribution of earthquake information but also better communication between the providers of the information (e.g., universities and government agencies) and the users. The spirit of this project was inherited by the ShakeMap (Wald et al. 1999, Fig. 1.1). ShakeMap is a map showing the distribution of ground-motion parameters which is produced automatically within a few minutes to an hour after a large earthquake. At present, ShakeMap is used widely by the USGS and other agencies as the basic information for taking emergency measures after a damaging earthquake. For this type of information to be useful, it is important to have close interaction between the providers and the users. One-way communication has only limited utility. In the CUBE project, the interaction was promoted by regularly scheduled meetings to discuss the effective use of real-time information, and in the event of large earthquakes, the feedback from the users concerning how accurately, rapidly and effectively the information was sent to the users and how the information was actually used for emergency operations. This feedback was extremely important for development of CUBE.



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+

Fig. 1.1 ShakeMap for the 1999 Hector Mine (M_w=7.1, California) earthquake. ShakeMap shows the intensity distribution computed automatically from the observed ground motion, and is usually distributed to the users within a few minutes to 1 hour after an earthquake.

The rapid progress of modern seismological practice, information processing, and data telemetry in recent years has made it possible to produce similar information in a matter of a few seconds, instead of a few minutes, after a large earthquake. This progress made earthquake early warning a realistic goal. To date, several warning systems are practically used in Japan (Shinkansen), Mexico, and Taiwan. In Japan, various methods were developed in the 2000s at JMA, Railway Technical Research Institute, and National Research Institute for Earth Science and Disaster Prevention (NIED) (Horiuchi et al. 2005, Tsukada et al. 2004, Nakamura and Saita 2007, this issue). In February, 2004, these methods were integrated and JMA started test distribution of early warning information to a limited number of organizations. Figure 1.2 shows the system, REIS (Real-time Earthquake Information System) developed at NIED. These are among the most sophisticated systems designed for general earthquake warning purposes.

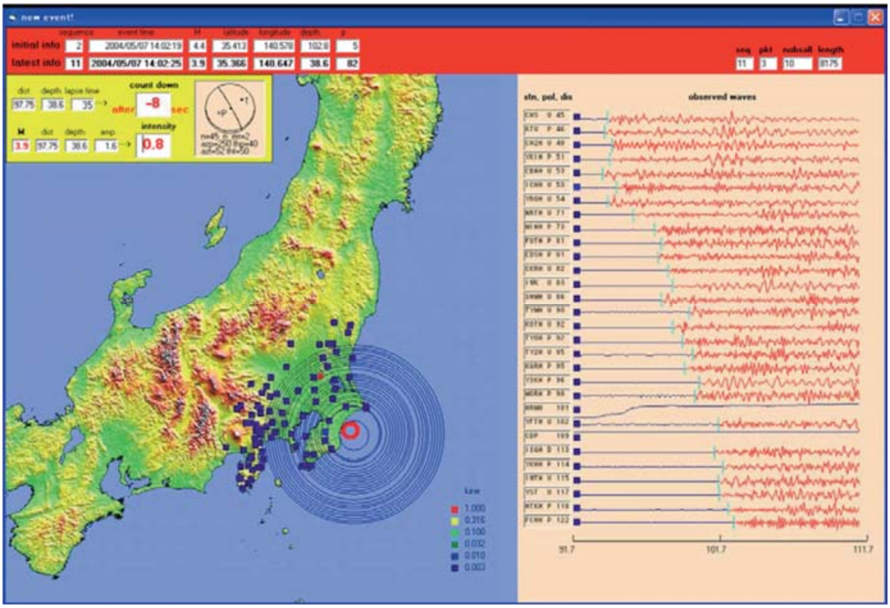


Fig. 1.2 This map was produced with REIS after an earthquake offshore of Boso, Japan. The wave front propagating from the epicenter is shown on the map. The estimates of the magnitude, intensity and the arrival time of strong ground motion at the receiver site are displayed. The seismograms at different locations are shown on the right. The users can tell when they should expect the onset of the strong shaking. (Courtesy of Dr. S. Horiuchi).

At present, the research is focused on how to best utilize the early warning information issued by these modern systems. It is still unknown how these systems will perform for very large earthquakes with large source dimensions, and for earthquakes at short distances (less than 30 km), but this development attracted public attention to the practical use of earthquake early warning. For example, a research group at Nagoya University is conducting an active interdisciplinary research on the practical use of earthquake early warning information. The interdisciplinary approach involving seismologists, engineers, social scientists, and emergency management personnel is critically important for successful implementation of early warning information in the future.

1.3 Implementation and Associated Problems

In the following, we list a few recent examples of practical use of earthquake early warning information.

1. UrEDAS has long been used for controlling the speed of Japanese Shinkansen after a large earthquake. During the recent Chuetsu earthquake in Japan (October 23, 2004, M_W=6.6), a UrEDAS located in the epicentral area issued an warning at 1 sec after the P-wave arrival at the site, which resulted in power shutdown and activation of emergency brakes on the train moving at a speed of 200 km/h near the epicenter (Fig. 1.3, Nakamura 2005). In this case, the train eventually derailed (no casualty) a few seconds later, and some media made somewhat negative reports to the effect that early warning was a failure. However, this view seems to be missing the point. It is remarkable that the early warning system worked as it is supposed to in such a short time. The system is not intended to prevent derailment; it is designed to slow down the train to minimize the impact of strong ground motion.
2. Motosaka et al. (2006) reports an experiment involving an elementary school in Sendai, Japan, to practice emergency exercises in response to an earthquake early warning to be issued by the JMA system. In this area, magnitude 7 earthquakes (Miyagi-Oki earthquakes) are known to occur offshore once every approximately 30 years. Motosaka et al. (2006) demonstrates the merit of such warnings for large offshore events.
3. Kanda et al. (2006) reports the use of the JMA early warning system in the construction site of a high-rise building in Yokohama. For the safety of the workers at the construction site, when an earthquake early warning is received at the site the workers are immediately notified the possibility of impending strong ground motion so that they can take proper safety measures such as stopping the elevators at the nearest floor and setting the tower cranes in a safe position.

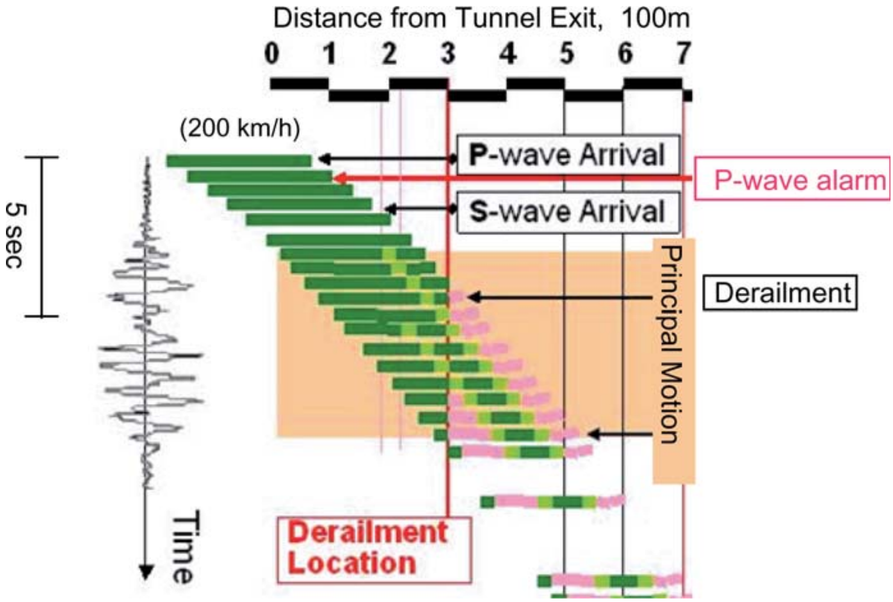


Fig. 1.3 Schematic diagram showing how UrEDAS worked during the 2004 Chuetsu, Japan, earthquake (M_W=6.6). The locations of the train are shown by green bars. The horizontal axis indicates the distance from the exit of a tunnel and the vertical axis is the time. A seismogram at a location near the train is shown along the vertical axis to indicate the ground motion. An alarm was issued at about 1 sec after the arrival of P wave. The ground motion was not very large at this time, and it took a few more seconds before the maximum motion occurred. The derailed cars are indicated by pink. (Courtesy of Dr. Y. Nakamura).

In addition to various technical issues, the overall reliability, the impact of false alarms and missed alarms, and the associated liability are among the issues being vigorously discussed these days. Needless to say that these issues are important, but at present when not many early warning system are in operation, it is somewhat difficult to fully understand its utility. It is probably most important at this point to accumulate more experience by testing various real-time systems for practical applications. Since we need to deal with complex earthquake processes and even more complex societal problems, it would be inevitable to encounter some difficulties associated with false alarms, missed alarms, and the resulting chaotic social responses. Accordingly, it would be better to start with practical use of earthquake early warning information for applications where false alarms and missed alarms will not cause catastrophic consequences. Introduction of any completely new concepts and methodology inevitably involves some risk. Nevertheless, considering the extremely serious impact of a large earthquake on modern metropolitan areas, introduction of effective short-term damage mitigation measures is desirable. Now that the technical feasibility has been demonstrated, it is most important to start exploring the effective use of earthquake early warning.

1.4 Basic Research on Seismology and Earthquake Early Warning

Besides its practical importance, earthquake early warning is an interesting subject of basic seismological research. After an earthquake has occurred, the wave propagation process is essentially governed by the crustal structure and the wave equation, and the uncertainty is expected to be fairly small. This is in contrast to the traditional earthquake prediction, in which the process is governed by many factors such as the distribution of stress, strength, the extent of interaction between different parts of the crust etc, and the prediction is inevitably very uncertain. In earthquake early warning, if the displacement field at the early stage can be measured accurately, its future development can be estimated fairly accurately using the wave equations and the known (at least approximately) crustal structure. To proceed with this method effectively, we need extensive research on the physics of earthquakes and on wave propagations in three-dimensionally heterogeneous media. Thus, the problem of earthquake early warning is not only an important practical problem but also an interesting scientific problem. Earthquake early warning may be one of few problems in which relatively accurate short-term predictions can be achieved. In most seismological problems, accurate short-term predictions are difficult because of the many unknown elements involved.

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2 Can Earthquake Size be Controlled by the Initial Seconds of Rupture?

Stefan Nielsen

Istituto Nazionale di Geofisica e Vulcanologia, Roma

Abstract

It has been argued that the dominant period T_p derived from the initial seconds of a seismogram, hence only depending on the initial phases of earthquake rupture, seems to scale with the final size of the earthquake. We provide a physical interpretation for the observed scaling and explain how the final earthquake size could be controlled by the initial phase of rupture.

2.1 Introduction

What are the chances that an initially small rupture continues to propagate and turns into a large earthquake? Propagation or arrest of earthquake rupture is ultimately controlled by the energy balance between the work of frictional breakdown and that of elastic stress (Aki 1979). Despite the above simple statement, the problem is not trivial: it can be shown that under given initial conditions, the balance strongly depends on the rupture history and modality. In particular, the energy flow essentially differs if the fracture propagates in the form of a large crack or a fracture pulse of variable size (Nielsen and Madariaga 2003). The strength of an earthquake barrier can be defined in terms of friction parameters and stress, but its capacity to stop rupture will critically depend on dynamic properties and essentially, on the characteristic length Λ of a fracture pulse (or in the case of a crack, its radius). As a consequence, the probability that a starting fracture will continue to propagate depends on the size Λ of the fracture pulse. For an average rupture propagation velocity v_r, the rise time can be defined as $T_r \approx \Lambda/v_r$, hence the probability of continued propagation should depend on the rise-time. It has been argued that a dominant period T_p can be derived from an earthquake seismogram; although T_p is derived from the initial seconds of the seismogram and hence only depends on the initial phases of rupture, it seems to scale with the final size of the earthquake

(Allen and Kanamori 2003; Olson and Allen 2005). These intriguing results immediately raise the question of causality: a physical justification should be found for this apparent predetermination of the earthquake size. We propose that T_p is linked to risetime T_r, and show how in T_r the initial phases of the rupture may affect the final size of rupture.

2.2 Statement of the Problem

The scope of early warning studies is to anticipate as much as possible the response to a potentially destructive event. The size of an earthquake should be determined as soon as possible in order to trigger a proper response, and reducing the delay of a few seconds only may be determining for the success of final size of an earthquake (in the probabilistic sense), even before the rupture propagation has ended. Note that we are not discussing the properties of the slow, quasi-static nucleation phase, but the early phases of dynamic rupture acceleration and advancement.

An earthquake is triggered on a fault at time t_0. At time t_1 the rupture has already propagated to a finite size A (Fig. 2.1), radiating a wavefiled which is captured by one or more seismographs in the vicinity of the fault at time t_3. Do the properties of rupture at time t_1 (and of the wavefield recorded at time t_3) carry some information on the probability that the fracture will continue to propagate until it reaches a final size B? If the answer is positive, which physical model of rupture is in agreement with such a statement?

2.3 Fracture, Barriers and Energy Concepts

The probability Π_p that an earthquake rupture continues to propagate is complementary to the probability Π_s that the rupture stops, i.e., Π_p=1- Π_s. In other words, we have to investigate the *stopping dynamics* of earthquake rupture in order to understand what mechanism could control the final size of rupture. Earthquake propagation stops when the rupture runs into a sufficiently strong barrier, so the first step is to quantify barrier strength.

The relative barrier strength should be defined in terms of energy balance, and several classical studies have treated the question of rupture propagation or arrest in term of fracture energy. The concept was originally developed by Griffith (1921). when describing the conditions under which a static crack becomes unstable and starts to grow. It was subsequently developed to more complex situations, including several cases of dynamic propagation. In all cases, the problem is essentially described as the balance between the loading conditions or fracture-driving force, on the one hand, and the energy dissipated by the fracture process or by the creation of newly cracked surface (fracture energy), which tends to resist crack propagation, on the other hand. When the applied load is sufficient to overcome dissipation, the crack propagates, otherwise it stops. The non trivial point is that the entity of fracture driving force available depends not only on the remotely applied load, but also on the geometry and scaling of the problem, in particular, the size of the preexisting crack.

Earthquake-stopping barriers were characterized, for example, in the Pioneer studies by Bouchon (1979) and by Aki (1974) for the Parkfiled, 1966 earthquake. Aki build his study on earlier theoretical work of Barenblat (1959) and Ida (1973) who described the fracture energy as a dissipation process taking place in a finite, cohesive zone around of the propagating fracture.

The size d of the cohesive zone controls the scaling of stress at the fracture tip, and, as a consequence the stress intensity factor K (in units of Pa $m^{1/2}$) and the fracture energy (usually named G, in units of J m^{-2}). Another length, the characteristic slip weakening distance δ_c, allows scaling of the dissipated energy G, as the work done by friction against slip inside the cohesive zone.

I will first recall the main relationships that allow to define energy flow during the propagation of simple fracture models, and argue that the distinction should be made between two independent estimates of the fracture energy. On the one hand we may define G_e as the energy flow into the fracture tip. G_e equates to the finite amount of elastic energy stored in the vicinity if the fracture tip, which is absorbed when the fracture advances of a unit length. Though G_e usually concerns a small region around the fracture tip, it depends on the load provided by the whole previous slip history on the crack faces, thus it cannot be defined a priori based on local fault properties. On the other hand, the dissipated energy G_w may be defined as the work against the friction excess during the initial, weakening part of slip, depending, in principle, on local friction parameters only. Obviously, the dynamic fracture process satisfies the energy balance so that at the available energy G_e and the dissipated energy G_w should coïncide during fracture propagation.

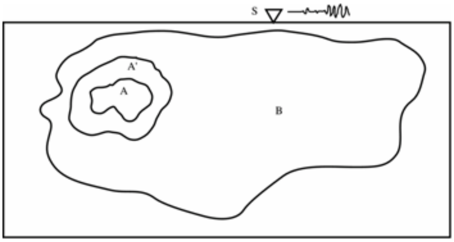

Fig. 2.1 Schematic representation of earthquake faulting process and formulation of the causality problem. Assume that in the source area, fracture has expanded into an area A at time t_a and continues to expand. The radiation produced by *A* at t_a reaches the receiver *S* at time $t_b > t_a$. At t_b the source has reached a larger area A' and continues to propagate. However, the signal arriving at *S* at time t_b only contains information on the early rupture patch *A*; it is not affected by A', all the less by the much larger area *B*, whose radiation will reach *S* at later times. The question is then: do the source properties in the initial area *A* affect the chances that rupture continues to grow and reaches a size *B*? If so, can such properties identified in the early radiated field reaching *S* at time t_b?

2.4 Defining and Quantifying Fracture Energy

Let's first define the dissipated energy G_w based the work against the friction excess during the initial, weakening part of slip, depending, in principle, on local friction parameters only:

$$G_w(\mathbf{x}) = \int_0^{D_c} \Big(\tau_f(\mathbf{x},\delta) - \tau_r(\mathbf{x})\Big)\, \mathrm{d}\delta = \int_0^t \dot{\delta}(\mathbf{x},\mathbf{t}')\, \Big(\tau_f(\mathbf{x},\mathbf{t}') - \tau_r(\mathbf{x})\Big)\, \mathrm{d}t' \tag{2.1}$$

where δ and $\dot{\delta}$ are slip and slip-rate, τ_w is the friction on the fault and τ_r is the relaxed (or minimum level) of the friction during slip. As usual, we can illustrate the G_w integral as the area below the initlal part of the frictional curve. For a simplified slip-weakening behavior as defined by Ida, where the friction drops linearly between the peak stress τ_y and the relaxed stress τ_r, the dissipation reduces to:

$$G_w = \tfrac{1}{2}\, D_c\, (\tau_y - \tau_r).$$

Let's now illustrate how the dissipated energy G_e may be estimated based on the fracture history instead. In certain cases knowledge of the previous slip history allows to compute the stress in the vicinity of the fracture tip and to derive the stress intensity factor *K*, which, in turn, allows to derive the the energy flow *G* per unit advancement of the fracture tip. If we consider only shear fracture (no opening), we may have anti-plane and in-plane motion (mode III and mode II, resp.), and the two intensity factors are defined as:

$$K_{III} = \lim_{r \to 0} \sqrt{2\pi r}\, \tau_{\perp}(r)\,, \tag{2.2}$$

$$K_{II} = \lim_{r \to 0} \sqrt{2\pi r}\, \tau_{//}(r)\,, \tag{2.3}$$

where r is the distance ahead of the crack tip and τ is the shear traction in the fracture plane, either parallel (//) or perpendicular ($\perp$) to the slip direction. Then the energy flow can be written, according to Irwin (1957), for a quasi-static crack:

$$G_e = (1-\nu)\,\frac{K_{II}^2}{2\mu} + \frac{K_{III}^2}{2\mu}$$

where μ is the shear stiffness and ν the poisson ratio. When the velocity of fracture propagation is not small, additional functions should be introduced to account for the dynamic propagation. For fractures propagating at a constant velocity, the additional dynamic terms can be evaluated analytically and we may write

$$G_e = (1-\nu)\,\frac{K_{II}^2}{2\mu}\, Y_{II}(v_r/\alpha) + \frac{K_{III}^2}{2\mu}\, Y_{III}(v_r/\beta)\,. \tag{2.4}$$

Broberg (1999) called Y_{II} and Y_{III} he Yoffe functions in memory of the pioneer studies where Y_I was defined (Yoffe 1951). A slightly modified form of the Yoffe functions called $F(v_r)$ is also found in Freund (1979) and Rice (2005). The Yoffe functions only depend on the dimensionless ratios of fracture velocity to wave velocity, and hence remain the same whether fracture takes place as an expanding crack, a steady-state self-healing pulse, a self-healing self-similar pulse or a rupture with more complex history:

$$Y_{II} = \frac{2B\,(1-B^2)\,\gamma_\alpha^2\sqrt{B^2-\gamma_\alpha^2}}{4B^3\sqrt{1-\gamma_\alpha^2}\sqrt{B^2-\gamma_\alpha^2}-(2B^2-\gamma_\alpha^2)^2} \tag{2.5}$$

for the subsonic case ($v_r < v_{Rayleigh}$), and for the intersonic case ($\beta < v_r < \alpha$)

$$Y_{II}^* = \frac{2B\,(1-B^2)\,\gamma_\alpha^2\sqrt{B^2-\gamma_\alpha^2}}{(\gamma_\alpha^2-2B^2)^2\sqrt{1+\frac{16(1-\gamma_\alpha^2)(B^2-\gamma_\alpha^2)B^6}{(\gamma_\alpha^2-2B^2)^4}}}\,. \tag{2.6}$$

With $B=\beta/\alpha$ and $\gamma_\alpha = v_r/\alpha$.The anti-plane function yields the much simpler expression:

$$Y_{III} = 1/\sqrt{1 - v_r^2/\beta^2} \tag{2.7}$$

Though *Y(.)* only depend on fracture velocity, the stress intensity factors *K(.)* vary greatly depending on the type and history of fracture, with high consequences on the energy flow.

For example, we an compare the stress intensity function for a mode III fracture, which can be derived according to expression (2.2), for some particular cases where an analytical expression is known. for the steady state pulse of length Λ:

$$K_{III} = (\tau_0 - \tau_r)\,\sqrt{2\,\pi\,\Lambda}$$

for an expanding, self-similar crack that has reached a radius of Λ (i.e., $\Lambda = t\, v_r$):

$$K_{III} = \frac{\sqrt{1 - v_r^2/\beta^2}}{\mathbf{E}(1 - v_r^2/\beta^2)}\,(\tau_0 - \tau_r)\,\sqrt{2\,\pi\,\Lambda}$$

where **E**(.) is the complete elliptic integral of the second kind, and finally, in the case of an expanding, self-similar pulse, that has reached a length Λ (i.e., $\Lambda = t\,(v_r - v_h)$):

$$K_{III} = \frac{\sqrt{\phi}\,\sqrt{\beta/v_r}\quad(\tau_0 - \tau_r)\,\sqrt{2\,\pi\,\Lambda}}{4\left(1 - \frac{v_h}{v_r}\right)\left(\mathbf{F}\left(\frac{\lambda}{\phi}\right) - \mathbf{\Pi}\left(\frac{1+\frac{v_r}{\beta}}{1-\frac{v_r}{\beta}}, \frac{\lambda}{\phi}\right) + 2\sqrt{\frac{\beta\phi}{v_r}}\mathbf{E}\left(\frac{\lambda}{\phi}\right)\right)}$$

where, for clarity, the notations

$$\phi = \left(1 + \frac{\beta}{v_h}\right)\left(\frac{\beta}{v_r} - 1\right)$$

$$\lambda = \left(\frac{\beta}{v_h} - 1\right)\left(1 + \frac{\beta}{v_r}\right)$$

have been introduced. As seen above, the stress intensity factor depends on fracture velocity and healing front velocity if a healing is present (in the case of the steady state pulse, rupture velocity does not appear explicitly in the above *K* expression, but only if *K* is written in terms of final slip instead of stress drop, see for example in Freund 1979).

Though the above examples concern a *limited* set of rupture modes, their properties apply to all fracture types; In all cases, the stress intensity is proportional to the square root of Λ, so that the energy flow *G* will be proportional to Λ, the size of the actively slipping fracture, and we can write:

$$G_e = \psi \left\{ \frac{vr}{\beta}, \frac{vr}{\alpha}, \frac{vh}{\beta} \right\} \frac{\pi (\tau_0 - \tau_r)^2}{\mu} \Lambda \quad (2.8)$$

though the functional form of φ varies depending on the fracture modality, the dependance of G_e on stress drop square $(\tau_0\text{-}\tau_r)^2$ and active fracture length Λ remains the same, even for complex fracture histories with no analytical conterpart. It is essential, however, that Λ in (2.8) describes the length of actively slipping rupture (rupture pulse), and not the length of fracture propagation (note, however, that in the case of crack-like rupture both lengths are the same).

As shown by Nielsen and Madariaga (2003), the presence of a propagating healing front in the fracture trail modifies the relationship between energy flow and propagation velocity, providing a self-locking mechanism for stopping fracture when the rupture front slows down. The Nielsen Madariaga (2003) solution correspond to a self-similar, expanding pulse, a fracture modality spontaneously developping under conditions where a healing front is triggered. Such conditions include the presence of a mild rate-weakening behavior in the friction law.

Steady-state fracture pulse of constant length were illustrated by Yoffe (1951), Freund (1979), Rice (2005) and Dunham and Archuleta (2005). The relevance of self-healing fracture pulses for earthquake faulting was also discussed in Heaton (1990) showing that kinematic inversions for several large earthquakes infer a systematically short rise-time T_r. Except for the case of intersonic fracture velocity illustrated in Dunham and Archuleta (2005), the nature of the steady-state solution is such that the kinetic wavefield around the fracture remains unchanged: this implies that no kinetic energy is radiated. As a consequence, the energy balance is greatly simplified energy flow reduces to a *locally* satisfied balance, where the energy dissipation is simply the product of slip by the dynamic stress drop. Indeed, the global energy balance for propagating fracture may be written:

$$\int_T \int_\Gamma \tau_0(\mathbf{x})\, \dot{\delta}(\mathbf{x},t) \mathrm{d}\mathbf{x}\, \mathrm{d}t = \int_T \int_\Gamma \tau_f(\mathbf{x},t)\, \dot{\delta}(\mathbf{x},t)\, \mathrm{d}\mathbf{x}\, \mathrm{d}t + \int_T \int_V \omega_{ksg}(\mathbf{x})\, \mathrm{d}v\, \mathrm{d}t$$

where Γ is the fault surface, ω_{ksg} groups the sum of kinetic, strain and gravity energy variations due to fracture, affecting volume V around the fault. Moreover, $\delta(\mathbf{x})$ is the slip at point $\mathbf{x}$, while τ_0 is the initial shear traction (prestress) and τ_f the frictional traction on the fault. The term on the left