https://ntrs.nasa.gov/search.jsp?R=19920002364 2020-03-17T15:21:57+00:00Z

(NASA-CR-186701) REAL-TIME EARTHQUAKE MONITORING: EARLY WARNING AND RAPID RESPONSE (NAS-NRC) 63 p

N92-11532

CSCL 08K

Unclas

G3/46 0040070

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REAL-TIME

Earthquake Monitoring

REAL-TIME EARTHQUAKE MONITORING

Early Warning and Rapid Response

Panel on Real-Time Earthquake Warning
Committee on Seismology
Board on Earth Sciences and Resources
Commission on Geosciences, Environment, and Resources
National Research Council

National Academy Press
Washington, D.C. 1991

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Support for this project was provided under general funds for the Committee on Seismology through the following agencies: National Science Foundation, Department of Energy, U.S. Geological Survey, Nuclear Regulatory Commission, Federal Emergency Management Agency, National Aeronautics and Space Administration, and Defense Advanced Research Projects Agency.

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Board on Earth Sciences and Resources
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2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

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CHARGE TO THE PANEL

The panel is to report on the subject of real-time earthquake monitoring, including recommendations on the feasibility of using a real-time earthquake warning system to mitigate earthquake damage in regions of the United States such as Southern California, Central California, the Pacific Northwest, and Alaska, and in other areas such as New Madrid and Charleston. If such a system is feasible and is practical for purposes of mitigation, recommendations should include systems specifications and cost estimates. Specific methodologies and uses for such a system in identified areas should be a high priority.

Systems for real-time warning of earthquake ground motions have been used for about two decades in Japan. The goal of the system in Japan is to predict ground motion in realtime and to use the information to mitigate the damaging effects of the ground motion with rapid transit systems in particular. Real-time warning of strong ground motions from earthquakes has not been addressed at the national level for the United States as a mitigation technique and is not included in the National Earthquake Hazard Reduction Program.

TABLE OF CONTENTS

EXECUTIVE SUMMARY 1
Early Warning, 2
Real-Time Earthquake Monitoring, 3

1 INTRODUCTION AND BACKGROUND 4
Existing Real-Time Seismic Systems, 5
Experiences in the United States, 6
Current California Seismic Networks and Capabilities, 11
Notes, 17

2 APPLICATIONS OF A REAL-TIME MONITORING SYSTEM 18
Early Warning, 19
Response During Shaking, 23
Rapid Postearthquake Information, 24
Tsunami Warning, 25
Volcano Monitoring, 26

3 DEPLOYMENT 27
Deployment Along a Targeted Fault, 27
Seismic Area, Source Unknown, 28
Areas of Low Seismic Frequency, 31
Note, 31

4 TECHNICAL FEASIBILITY 32
Data Collection, 32
Data Processing, 33
Data and Information Dissemination, 34
System Costs, 34
Management Issues, 35
Notes, 36

5 **NONTECHNICAL CONSIDERATIONS** 38
System Evaluation, 38
Cost-Benefit Analysis, 39
Alternative Choices, 39
Public Perceptions, 40
Life and Safety, 41
Facilities: Automatic versus Manual, 42
False Alarms, 42
Liability, 44

6 **OTHER REPORTS** 45

7 **CONCLUSIONS AND RECOMMENDATION** 48

REFERENCES 50

EXECUTIVE SUMMARY

The ability to forecast closely the time, place, and magnitude of an earthquake has proved an elusive target. But although prediction remains a goal for the future, present technology is entirely capable of recording and processing data so as to provide real-time information, enabling people to mitigate somewhat the earthquake disaster. More specifically, this new technology has the potential of determining the magnitude of an earthquake while it is still in progress and of relaying this information to nearby communities before the onset of damaging shaking. Several simple real-time systems are currently operational in Japan and elsewhere.

Public sensitivity to earthquakes is now quite high, and the availability and installation in California of a number of earthquake warning devices (actually, devices that advise of an earthquake in progress) indicate that much of the public perceives them as useful.

Real-time warning of strong ground motion from earthquakes as a damage mitigation technique has not been addressed at the national level, nor is it currently included in the National Earthquake Hazard Reduction Program.

In view of the new technologies available and the increase in public awareness, the Committee on Seismology asked a study panel to report on the subject of real-time earthquake monitoring—the feasibility, costs, and possible mechanisms for establishing such a system.

With adequate sensor coverage and distributed processing, two types of real-time information are feasible:

1. Early warning system (EWS)—a few seconds to a few tens of seconds of warning before the onset of severe shaking, depending on the distance from the epicenter and

2. Immediate postearthquake information (real-time earthquake monitoring RTEM)—within minutes of an earthquake, actual measurements of the severity of shaking and therefore potential damage in populated and other sensitive areas and transmittal of this information to emergency response groups.

Although it is clear that the technology for such a system exists, or can readily be developed, it is less certain that such a system is acceptable to potential users without familiarization and demonstration.

Early Warning

For the assessment of the feasibility and desirability of an EWS, the panel relied heavily on the results of a survey conducted by the California Division of Mines and Geology (CDMG), which canvased more than 150 institutions such as large and small companies and public facilities. A few potential users saw immediate application; for example, early warning would allow people in offices or pupils in schools to duck for cover under desks. The responses from other companies, however, were equivocal and focused on two major problems:

1. The uncertain costs of response to a false positive—that is, if the ground shaking is below the damage threshold. In these cases, shutting off utilities or services would be potentially disruptive and costly. The report also notes the absence of a reliable method of measuring the cost of a false alarm.
2. The insistence by some users on a human link between the first alert and any action. Because of the short times involved (10 seconds or so) and the documented poor performance of human operators in rarely occurring events, the panel does not consider this option practicable.

In our view, the "market survey" technique is not a reliable method for assessing the utility or acceptance of a new product or concept. It is clear, therefore, that widespread use of any EWS would have to be preceded by a program of education and a demonstration phase. Then, as experience is gained, the model would be refined, presumably by scaling damage estimates derived from the more frequent, smaller earthquakes. During this period, potential users could assess the reliability of the system.

Some users would probably adopt the system immediately, especially those whose false alarm costs were perceived to be less than the potential savings. Once

a system is operational, its utility would become clearer to many other potential users.

Real-Time Earthquake Monitoring

Virtually the same system of sensors and processors used in an EWS will also allow a rapid assessment of areas of highest damage. (We assume installation of an areal distribution of sensors in addition to linear arrays along targeted faults.) Because large earthquakes frequently disrupt not only power but also telephone communications, reliable information on damage is commonly not available for many hours, even days. With an RTEM system in operation, emergency service personnel would know which roads or bridges are likely to be badly damaged and which areas were subjected to the most severe shaking. In addition, early warning of large aftershocks can save the lives of rescue personnel who enter damaged and unstable structures. A prototype of such an EWS was installed by the U.S. Geological Survey (USGS) following the Loma Prieta earthquake of 1989 and provided warnings of 12-20 seconds of aftershocks to workers on the collapsed I-880 (Nimitz) freeway.

Because a well-designed system can provide both early warning and immediate postquake information, we conclude that the potential benefits for hazard mitigation justify the installation of a pilot system. The technology is available, or at least so near state-of-the-art that it can readily be developed. Some new software will be required, but a number of researchers are already working along these lines.

We therefore recommend the installation of a prototype system. Probably the most efficient course would be to upgrade one of the existing (California) networks. This plan would take advantage of an existing infrastructure and would then build on experience. During the initial phase, many companies could and should use the provided (multilevel) signals for demonstration or evaluation only. Moreover, the system should include both research and evaluation activities so that it can be modified and improved as experience is gained. Because the system would be flexible and grow as knowledge is accumulated, detailed specifications and cost estimates are impractical at this time.

1
INTRODUCTION AND BACKGROUND

The advent of low-cost, high-speed computers and of rapid data transmission systems has made a real-time earthquake monitoring (RTEM) system a technical feasibility. In the event of a major quake such a system could provide: (1) warning times ranging from several seconds to tens of seconds to areas 10 or more km from the epicenter, (2) estimates of local intensities while the quake is in progress or within minutes after, and (3) rapid and reliable postquake information to guide rescue and relief efforts.

Public sensitivity to earthquakes, at least in California, has recently been heightened, partly by an increase in the number of quakes in the Los Angeles area, partly by the U.S. Geological Survey (USGS) forecast that major earthquakes will occur in the next decades, and especially by the Loma Prieta earthquake of October 17, 1989. Earthquake warning devices being installed in a number of schools illustrate this sensitivity.

Immediately after an earthquake, the same network that disseminated the warning could inform the relevant authorities where the greatest damage could be expected. Traffic patterns and power and water distribution could be modified, and emergency service units could be deployed more rapidly and accurately. The potential of this prompt postquake information is highlighted by the confusion about the epicentral location and damage estimates for recent California earthquakes (e.g., Whittier Narrows and Loma Prieta).

Many existing seismic networks telemeter data to a central processing site, where hypocenters are calculated automatically by computer. There are three such independent networks in Southern California alone. As presently constituted, these are not RTEM networks, but they could form a nucleus on which to build.

Requirements for an effective RTEM system are: (1) it must be hardened so that no components fail during the earthquake, (2) the sensors and the transmission system must have a sufficient dynamic range, (3) broad-band sensors are required

for magnitude estimates, and (4) a high-speed computer (or distributed processing for larger networks) is needed for rapid determination of the hypocenter and the magnitude. The computer in turn must be able to alert information centers and other users requiring timely information.

The value of an RTEM network during a major earthquake can be inferred from the responses to the Loma Prieta quake (M=7.1).[1] The breakdown in communications systems and the lack of reliable information from the epicentral area would have had more serious consequences had the quake been larger—for example, M=8—or had the epicenter been nearer a populated area.

Existing Real-Time Seismic Systems

Several simple systems for real-time monitoring or warning of seismic shaking have already been designed and implemented. The most advanced of these are in Japan, where several different and independent systems have been deployed.

Best known is the system operated by Japan Railways to stop the high-speed Bullet Train in the event of strong shaking, thereby minimizing the chance that the train would traverse a damaged section of track. The original system, installed more than 20 years ago, used a simple trigger to cut power when a specified level of acceleration was exceeded. It has since evolved into a more sophisticated network of sensors capable of providing advance warning of shaking when the epicenter is some distance from the rail line. This system is used exclusively for the Bullet Train and not for other segments of Japanese society. More complete discussion of this system is given by Nakamura and Tucker (1988) and Holden *et al.* (1989).

The Japan Meteorological Agency (JMA) operates an extensive real-time seismological center both to predict the expected Tokai earthquake (M=8) and to provide the real-time forecasts of local tsunamis (Tsumura, 1988). The tsunami warning system is a particularly good illustration of the importance of real-time seismology. Following a large earthquake, one of six JMA regional centers rapidly analyzes seismic information to determine whether a tsunami advisory should be issued. This process generally requires 10-15 minutes; JMA is attempting to reduce that time to 5-8 minutes.

Approximately 120,000 people were killed and 400,000 homes burned in the great 1923 Kanto earthquake in Tokyo. Consequently, ignition of fires during earthquakes has been a major concern in Japan, and Tokyo Gas operates a 31-

station seismic network to control flow in its supply network in the event of strong shaking (Holden *et al.*, 1989).

A three-station seismic system is also operated by Teito Rapid Transit Authority to stop Tokyo subway trains in the event of strong shaking. A system of local sensors used in high-rise buildings in Tokyo causes elevators to stop at the nearest floor in the event of an earthquake. Local sensors activate prerecorded messages on loudspeaker systems in schools and other public facilities.

Telemetered seismic networks are also operated by several Japanese universities, and a three-component digitally telemetered network is operated in the Tokai region by the National Research Center for Disaster Prevention (NRCDP). These networks are designed primarily to record and monitor small earthquake activity. The NRCDP network has focused on the problem of monitoring seismic activity in the Tokai region, and automated data analysis and warning systems have been developed to provide rapid response to changes in microearthquake activity.

Within the United States are several simple real-time systems, mostly in California. For example, the Bay Area Rapid Transit (BART) has several seismic sensors that telemeter information to the control center to stop subway trains during an earthquake; and all California elevators are required to have automatic shut-down devices similar to those in Tokyo. Seismic sensors shut down about 25 percent of California elevators; sensors that detect earthquake-caused malfunctions in counterweight tracking systems shut down the rest.

In Alaska, a simple system based on P-wave detection[2] is designed to shut down the trans-Alaska pipeline during a quake.

Experiences in the United States

Several U.S. earthquakes illustrate the type of real-time seismic information that would be valuable for human response. This discussion is not inclusive; it merely provides representative examples.

San Fernando

At 6:07 a.m., February 9, 1971, the Los Angeles metropolitan region was jolted awake by an $M = 6.5$ earthquake beneath the San Gabriel Mountains, which lie along the northern margin of this densely populated area. Strong shaking

occurred throughout the San Fernando Valley, the eastern San Gabriel Valley, and the northern Los Angeles basin, a region with a population of several million. Seismologists at the California Institute of Technology hurriedly drove to work so that they could analyze data from the earthquake.

Despite the strong shaking that occurred at Caltech's Seismological Laboratory, the seismic network continued to work throughout the earthquake sequence, and seismologists were able to determine that the earthquake's epicenter was beneath Newhall, a relatively sparsely populated area in the San Gabriel Mountains. This information was relayed to California state emergency response personnel, and helicopter surveillance of this region was initiated. Unfortunately, the earthquake occurred on a thrust fault that slanted upward to reach the surface in the densely populated San Fernando Valley, approximately 10 km south of the epicenter. Heavy damage occurred in this area, including 56 fatalities, largely from the collapse of the Sylmar Veteran's Hospital.

Because of the heavy damage, communications from this region were minimal, and at least 3 hours passed before official recognition that the Veteran's Hospital had collapsed. If real-time locations of aftershocks or real-time information regarding ground motion amplitudes in the metropolitan area had been available, seismologists could have focused better the activities of emergency response personnel.

Even with a modest improvement in equipment and analytical capability, scientists would have obtained a focal mechanism within minutes. This would have shown the thrust-fault nature of the event and thus directed attention for damage to the area south of the epicenter.

Imperial Valley

The difficulties of coordinating emergency response were apparent during the October 15, 1979, $M=6.5$ Imperial Valley earthquake. The epicenter was in Mexico, several km south of the international border, but the rupture propagated some 40 km to the north along the Imperial fault, causing substantial damage to the Imperial Valley region of California. The epicentral location provided by the California Institute of Technology suggested that the earthquake may not have required a major response in the United States, and it was several hours before it became clear that the most intensely shaken areas were north of the border. Here again, prompt data on fault propagation and strong ground motions would have aided emergency response activities.

Whittier Narrows

The earthquake at Whittier Narrows (M = 5.9) occurred on Thursday, October 1, 1987. It was followed by an aftershock (M = 5.5) on Sunday, October 4. Damage was greatest in buildings of poor construction and in areas of poor foundation conditions.

Even though damage from the Whittier Narrows event was relatively small, communication of information was slow and inaccurate. Three separate emergency systems (in three counties) were on the air reasonably promptly, but they often broadcast conflicting or incorrect information, simply because there was no reliable reporting from or about the damaged areas.

Another obvious but important lesson from this quake is that damage was minimized and recovery speedier in facilities that had established plans and procedures for such emergencies.

Alaska

One way to use seismic information in real time is to give a warning in the seconds between the origin time of an earthquake and the arrival time of strong shaking at a given location. Because the area of strong shaking is large for very large earthquakes, the chance of achieving a long warning time (tens of seconds) is best in the event of very large earthquakes. Several historic earthquakes in the United States have fault dimensions large enough to permit substantial warning in real time.

The M = 8.6 March 28, 1964, Alaskan earthquake is the largest in U.S. history, and it seriously damaged (and in some cases completely destroyed) a number of Alaskan communities. Death and destruction were caused by building collapse from ground shaking, soil failures, tsunamis, and seiches. The region of heavy shaking extended along 600 km of the coast. Had a seismic warning system been operational during this earthquake, several areas would have had warning times in excess of tens of seconds, and some would have received warning more than 2 minutes prior to the shaking. Destruction by this great quake was minimized only by the sparse population. There is evidence that similar great subduction earthquakes occurred prehistorically along the western parts of Washington, Oregon, and northern California (Heaton and Hartzell, 1987; Atwater, 1987).

California

The 1857 and 1906 M = 8 earthquakes on the San Andreas fault in southern and northern California, respectively, both ruptured over fault lengths of more than 300 km. Up to tens of seconds of warning could have been provided to many strongly shaken regions.

New Madrid

In 1811 and 1812, a sequence of large earthquakes struck the then sparsely populated Mississippi Valley region of the central United States. Three of the earthquakes caused particularly intense shaking near New Madrid in southern Missouri, but they were large enough to cause damage 400 miles away and to be felt in Canada, Washington, D.C., Boston, and New Orleans (Nuttli, 1973).

The occurrence of a similar quake somewhere in the central or eastern United States presents a particularly challenging problem for earthquake response. Significant warning times should be possible for imminent shaking for earthquake sequences of this type. The prompt relay of damage assessment could be even more important than the warning.

Because of the many jurisdictions that are involved in such a widespread disaster, and because of the relative inexperience with earthquake emergencies in the eastern and central states, it could take days before the overall nature of such a disaster could be assessed with existing systems. The rapid use of seismic information to assess the overall character of such earthquakes will be vital for initiating the proper level of response.

Hawaii

A rather dramatic use of real-time seismology comes from the Hawaiian Volcano Observatory (Carl Johnson, USGS, personal communication). In July 1987, a swarm of microearthquakes being monitored by Robert Koyanagi was determined to be hypocentered just under the site where a field party was deployed. These hypocenters were interpreted as recording the upward movement magma. The field party was therefore warned and was evacuated shortly before the eruption of a dangerous curtain of fire on Kilauea's east rift.

Loma Prieta

At 5:04 p.m. on October 17, 1989, an M = 7.1 earthquake centered near Loma Prieta caused substantial damage not only in the near epicentral region, Santa Cruz and Los Gatos, but also in vulnerable areas in the San Francisco Bay region. Fortunately, the region of intense shaking in the vicinity of the epicenter itself was relatively sparsely populated.

Major damage in the bay area affected highway I-880 (which had not been reinforced to the latest earthquake resistance standards), the bay bridge, and San Francisco's marina district, which is built on fill. Other less-publicized damage areas include I-280, the Embarcadero freeway, and interchanges along Route 101. In addition, although many buildings in San Francisco and Oakland did not collapse, they cannot be repaired. Major damage in the epicentral area was widespread, especially affecting older structures in Santa Cruz. Recorded ground accelerations in the epicentral area did not exceed 0.7 g,[3] and the duration of shaking was relatively short. Even so, communication systems were completely disrupted for up to 24 hours.

The cost of damage from the Loma Prieta earthquake is some 60 lives lost and at least $6 billion in property damage. Most structures designed to be earthquake resistant performed well[4] and thus kept the casualty toll low. Had the Loma Prieta earthquake been an M = 8 or larger, the communications blackout would have been more severe and the severely damaged area much larger. Lacking an RTEM system, emergency service response groups would have had little guidance on which roads or bridges were impassable or which areas were potentially devastated.

An important follow-on of Loma Prieta is a working demonstration of an early warning system. After the quake, the USGS installed sensors in the epicentral region that triggered a warning system wherever an aftershock exceeded M = 3.7. Data were radioed to the USGS at Menlo Park and analyzed in real time. Warnings were broadcast instantaneously to sites on the I-880 freeway in Oakland and other locations in the bay area. Advance warning for P waves was 8-12 seconds and for S waves 17-27 seconds, enabling rescue crews at the partially collapsed sections of the freeway to leave before shaking began.

From a review of the Loma Prieta event, it is clear that the disruption of communication systems was a critical effect. For example, it was known within a short time that the epicenter was in the Santa Cruz/Los Gatos area some 50-60 miles south of San Francisco. Given the known damage in San Francisco, it would have been reasonable to infer massive damage requiring major assistance

in the epicentral area (an RTEM would have given this information). But no emergency vehicles or helicopters were dispatched promptly, and the extent of the damage to Santa Cruz was not known for a full day. Even without an RTEM, the response systems should have focused on the epicentral area sooner.

Current California Seismic Networks and Capabilities

The best-developed U.S. seismic networks are in California, but all existing systems lack essential elements for use in real-time response. The factors pertinent to the recording and use of seismic data are discussed in the *National Seismic System Science Plan* (Heaton *et al.*, 1989) and *Assessing the Nation's Earthquakes: The Health and Future of Regional Seismograph Networks* (National Research Council, 1990).

Table 1 lists the major seismic networks currently operating in California. Although these networks serve a variety of purposes, the largest efforts are divided between regional networks (which are largely short-period, high-magnification, telemetered seismic networks) and the strong motion networks. We will discuss these two categories of networks separately.

Regional Seismic Networks

The 360-station network in central and northern California operated by the USGS (Menlo Park) and the 240-station network in southern California operated cooperatively by the USGS (Pasadena) and the California Institute of Technology are the two largest regional seismic networks in the United States. Both networks were designed in the 1960s and 1970s and deployed in the 1970s and early 1980s primarily for systematically mapping the fine structure of the spatial and temporal patterns defined by the tens of thousands of small earthquakes that occur in California each year.

Seismic signals are telemetered in analog form to central recording facilities in Menlo Park and Pasadena, where they are digitized at 100 samples per second. Because of the volume of incoming data, only the time periods with earthquakes are saved. A detection algorithm is applied to the digital data and detected events are analyzed using a computerized system to pick seismic arrivals and to locate epicenters. An earthquake catalog comprising seismic arrival times and seismograms is archived on magnetic tape.

TABLE 1. California Seismic Instrumentation

TELEMETERED HIGH-GAIN NETWORKS	APPROXIMATE NUMBER OF STATIONS
USGS Central and Northern California	360
USGS/Caltech Southern California	240
University of California, Berkeley	20
University of Southern California	30
Others	75
STRONG-MOTION ACCELEROMETERS	
California Division of Mines and Geology	500
U.S. Geological Survey	250
Large buildings in Los Angeles	500
Pacific Gas and Electric	90
University of Southern California	80
California Dept. of Water Resources	70
Univ. of Calif., Los Angeles	35
Los Angeles Department of Water and Power	35
Metropolitan Water District	30
Southern California Edison	30
Others	300

In addition to maintaining a record of some 30,000 earthquakes per year, the systems have been expanded to locate earthquake epicenters automatically and promptly (approximately 5 minutes). The networks are staffed only during normal working hours, but simple alarm systems alert the staff (many of whom carry radio pagers) to all significant events. Information is transmitted promptly to a number of organizations ranging from the California Office of Emergency Services to private corporations such as the Santa Fe Railroad. Information is also provided to the news media.

Several other telemetered seismic networks are operated in California by the University of California from its Berkeley and San Diego campuses, the University of Southern California, the California Department of Water Resources, the Pacific Gas and Electric Company, and several geothermal energy companies. Information is commonly shared among the networks.

Strong Motion Networks

Numerous strong motion accelerographs are deployed in California primarily to record ground motions. Although digital accelerographs are becoming more common, the vast majority of strong motion instruments record in analog form on photographic film. Most systems are designed to record only during strong shaking and are typically triggered after 0.01 g has been exceeded on the vertical component. If the records are deemed significant (typically ground accelerations exceeding 0.05 g), they are digitized and analyzed. The primary use of these networks has been to provide data for the design of engineered structures, but the records have also been important in seismological modeling studies. Because the networks' missions differ, there has been little coordination between management of the strong motion networks and that of the regional seismic networks.

Although private organizations maintain many strong motion instruments to record the performance of structures, they also maintain several networks for fundamental research data. The largest, comprising some 400 accelerographs, is operated by the California Division of Mines and Geology under the auspices of the Strong Motion Instrumentation Program.

The USGS maintains a network of approximately 250 strong motion accelerometers in California. These instruments are owned by several agencies, including the USGS, the Bureau of Reclamation, the U.S. Army Corps of Engineers, and the California Department of Veterans Affairs.

The Department of Engineering at the University of Southern California, supported by the National Science Foundation, has installed a network of approximately 80 stations in the Los Angeles metropolitan area.

Limitations of Existing Networks

The characteristics of both the regional seismic networks and the strong motion networks are dictated largely by their goals.

The principal goal of regional networks is to detect and locate large numbers of small earthquakes. Thus, it is imperative to detect and determine the arrival time of P waves from as many sites as possible. When these networks were developed, the only practical way to achieve this goal was continuous telemetering of high-frequency high-gain seismic signals from as many sites as possible. The need for continuous telemetry of high-frequency data dictated the use of analog frequency modulated telemetry systems that have a dynamic range of about 2 orders of magnitude (40 decibels). The seismometers are designed to respond only to high-frequency motions (0.5 to 20 hertz) because natural seismic noise peaks at approximately 6-second periods and the dynamic range of the analog telemetry system is limited.

Figure 1 shows the range of amplitudes and frequencies recorded by typical stations in the southern California network. The size of ground motions is shown as a function of frequency for different earthquake magnitudes and observer distance. The initial P-wave times can be obtained for nearly all earthquakes greater than approximately $M = 2.0$. Ground motions, on the other hand, cannot be recovered for events larger than about 3.5 because the system is overdriven and the instruments go off scale. The restricted dynamic range of the analog telemetry system (2 orders of magnitude) therefore severely limits the range of amplitudes that can be recorded. Even if telemetry were not a consideration, the effective dynamic range of the seismometers within current networks is less than 5 orders of magnitude (100 decibels). Furthermore, many existing networks typically record only the vertical component of ground motion. Without horizontal ground motion data, it is difficult to interpret the S waves, which are typically the most important component of strong motion.

The sheer volume of data produced by the southern California seismic networks has necessitated development of complex data processing and storage procedures. Limited resources have inhibited the simultaneous development of systems to make the data easily and immediately accessible.

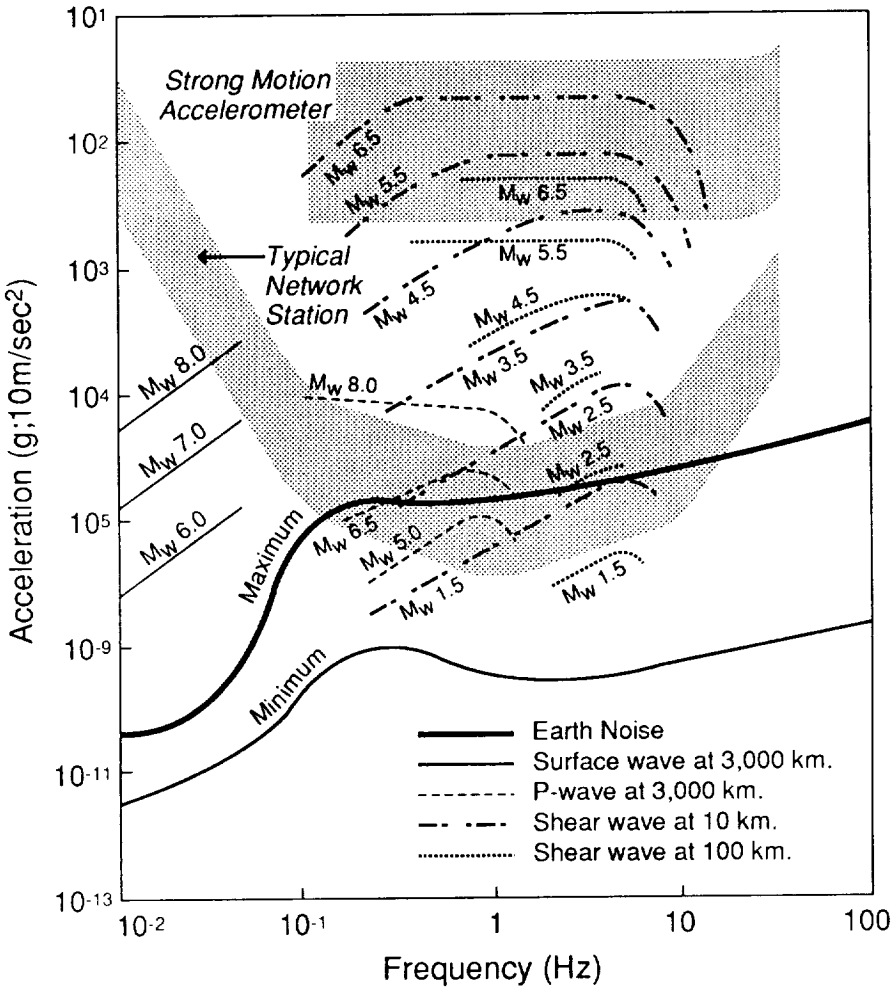

FIGURE 1. Earthquake accelerations. This figure shows the expected accelerations produced by a range of magnitude earthquakes (moment magnitude M_m) as a function of frequency. The range of operation of the typical existing California network station and typical strong motion station is indicated by the striped area. The curves marked -120 and -160 dB indicate constant power spectral levels of acceleration of 10^{-12} and 10^{-16} $(ms^{-2})^2/Hz$, respectively. Note that many earthquake motions are not within the range of existing instruments in the networks (after Heaton *et al.*, 1989).

The principal goal of strong motion networks is to provide data for engineering designs. With few exceptions, strong motion data are not telemetered, and the records are collected and processed by hand. It commonly takes weeks or months before they are available. This delay is not critical to engineering design studies, but on-scale records of ground shaking are rarely, if ever, available during or shortly after significant earthquakes.

Thus, as can be seen in Figure 1, many southern California earthquakes in the magnitude range of about 3.5-5.0 are too small to be recorded by many (probably most) existing strong motion accelerographs and too large to be recorded by existing telemetered seismic networks. The problems of dynamic range, bandwidth, and cumbersome data manipulation make difficult any rapid response by the current systems. Yet many interests are increasingly demanding information on the size of the earthquake, the causative fault, and the potential for additional seismic activity as soon as possible. Strong motion stations have recently been added to the southern California network to provide better response during significant quakes.

Vulnerability to Earthquake Damage

The existing strong motion networks are designed specifically to recover ground motion information from damaging earthquakes and hence are hardened to severe ground shaking. The telemetered seismic networks, on the other hand, are vulnerable. The seismic telemetered network in southern California did remain operational during the M=6.5 San Fernando earthquake and the M=5.9 Whittier Narrows earthquake, but a number of subsystems within these networks could easily have been damaged by this amount of ground shaking (Given, 1989). In particular, ground-based microwave and commercial telephone telemetry systems can be interrupted by strong shaking, as they were during the Loma Prieta earthquake. Furthermore, computer-based data analysis and alarm systems can be rendered inoperable by power failures or physical damage to the computers. Many of these problems can be anticipated and their potential impact minimized, but to date the survivability of existing telemetered seismic networks during damaging earthquakes has not been given high priority.

Notes

1. M=7.1 means magnitude 7.1 on the Richter scale. This notation is used throughout the report.

2. Earthquakes generate two types of seismic waves that travel through the body of the earth. The P, or primary, waves are compressional and travel faster than the S, or secondary, waves that are shear waves and are the most destructive. The interval between the arrival of the P and S waves is therefore proportional to the distance from the quake's epicenter, and a device that detects the arrival of P waves warns an observer that larger S waves will arrive some seconds later.

3. Incidents related by a number of people in the Summit Road area suggest accelerations of 1g or more.

4. A notable exception was the recently built Hyatt Regency in Burlingame.

2
APPLICATIONS OF A REAL-TIME MONITORING SYSTEM

Waves originating from a seismic source can be recorded continuously at nearly any given location, and the data so obtained transmitted to any other location. If the sensing station is substantially nearer the epicenter than is the responder station and the time delay of data processing and transmission is short, the responder station will receive information about the seismic waves before their actual arrival. This is termed an "early warning." The warning time will decrease as the distance between the sensing and responding stations decreases and will decrease as the data processing and transmission times increase. When the processing and transmission times are greater than the travel time of the waves from the sensing to the responding site, the information about the seismic event will not be available until after the arrival of the seismic waves. Such is the situation today.

The receipt of seismic data at a particular responding station is actually a time continuum (see Table 2). The receipt times are classified broadly as postearthquake information and real-time monitoring. Real-time monitoring is further subdivided into early warning and alerting. Table 2 also indicates some of the possible actions that might be initiated (though possibly not completed) within the given time. The table may be helpful in visualizing the difference between postevent seismic information and real-time seismic monitoring.

A modern monitoring system could provide for both early warning and rapid information. In more detail, the application of a monitoring system could provide: (1) early warning, including both automated and human response, (2) response during shaking, (3) rapid postearthquake information, (4) real-time probabilistic advisories, (5) tsunami warning, and (6) volcano monitoring.

TABLE 2. Possible Action Versus Time of Receipt of Seismic Data Before and After Arrival of Strong Shaking

	Time	Action	Classification
After Arrival	30 min.	Deploy additional resources	Post event information
	1-30 min.	Determine regional response, deploy resources	
	1-15 min.	Display/review damage estimates & response options, deployment of local units	
	0-1 min.	Display event information	Real-time monitoring
Before Arrival	0-2 sec.	Activate automatic devices, EDU's	
	2-5 sec.	Duck and cover	Alerting
	5-10 sec.	Alert emergency response personnel, mitigate manual safe shutdown procedures—industrial, lifeline, law enforcement	
	10-30 sec.	Complete manual shutdown procedures	
	>30 sec.	Evacuate hazardous areas	Early warning

Early Warning

Automated Response

The most effective use of earthquake early warning information is to activate automated systems. Automatic response maximizes the time available to initiate or complete the intended action. Many automated operations, such as the retraction of heads in a computer disk file or the shutoff of electrical power or a fuel supply line, can be completed in a matter of a few seconds. Other operations, such as starting backup power generators or safely shutting down certain

manufacturing processes, can be initiated quickly, but they might not be completed before a strong ground motion arrives.

Automated uses can be grouped as: (1) facility applications or (2) production applications.

Facility applications include switching off plant site power or natural gas and opening doors to remove fire fighting equipment prior to strong ground shaking. For electrical utilities, electrical fires at substations could be avoided by tripping the station, although doing so would entail a blackout following a false alarm. At some facilities, depressurizing systems containing flammable substances could reduce the fire hazard. Such applications generally require a warning time ranging from a few seconds to 10 seconds.

Production applications include the shutdown of pipelines, controlled shutdown of production processes, diversion of incoming aircraft, and computer applications (e.g., controlled shutdown, saving of vital information on a disk, moving of disk heads away from the disk surface). The time required to effect such operations varies for different operations and equipment. For many operations, securing or stopping potentially dangerous or easily damaged equipment can be accomplished in a few to 15 seconds. However, rapid shutdown could cause damage comparable to that resulting from the shaking. Thus, the consequences of false alarms must be considered. Other operations would require minutes to complete mitigating action, but even then, damage might be minimized if action could begin before the strongest shaking.

Human Responses

Earthquake early warning can sometimes be used to initiate a direct human response. The response can be an action to enhance personal safety or control a potential hazard.

Responses of personnel range from evacuating buildings (rare) to rapid personnel safety action within buildings (nearly "automatic" if personnel are well trained) to automatic public message broadcasts.

A warning time of 15 seconds or less would not, in most cases, allow sufficient time for building evacuation. Moreover, evacuation is contrary to the common advice *not* to exit a building during an earthquake. However, for a distant great earthquake, sufficient time for evacuation is possible. For great quakes, radio/TV stations could broadcast a prerecorded earthquake advisory. In Japan, public loudspeakers are activated automatically to advise occupants of large buildings of an earthquake in progress.

Actions to enhance personal safety, such as seeking cover under a strong desk or table or moving away from hazardous equipment, can be taken with an alert time of only a few seconds. School children, office workers, or factory workers

who have been drilled in the appropriate action will respond quickly. An automated alert system in this situation is more desirable than a spontaneous human announcement because it is the same each time, and the responder can be drilled accordingly. This type of alert can reduce panic. The automated alert could be supplemented by later instruction on subsequent actions, for example, orderly evacuation.

Human Intervention

In some instances, a human responder may be inserted intentionally into the early warning loop to provide additional intelligence and flexibility of response. It is interesting to note that a majority of the firms participating in a recent California Division of Mines and Geology survey (Holden *et al.*, 1989) felt that human intervention would be necessary in using early warning information. This perception led to a desire for longer early warning times that, in turn, greatly affected the results of the cost-benefit analysis. Whether the perception is justified, it appears that many users of real-time earthquake information would initially act upon the information only after it was filtered by human intervention.

Note that time is required for human intervention *with or without* early warning information. Thus, the real question is whether the *additional* response time provided by early warning is beneficial and whether the existence of an early warning or alert can decrease the human response time required.

Two important aspects of human intervention are the effects of indecision and the absence of key personnel.

Uncertainty about the nature of an event will cause indecision. Most people will not be able to accept the thought that so rare an event as a major earthquake is in progress. Then, after initial denial, they may not be sure whether the quake is large enough to warrant an emergency response. At best, this indecision will waste valuable response time; at worst, it can negate the entire system.

Key emergency response personnel may not be on duty when crucial decisions must be made. This also wastes response time. Even when key personnel are on hand, they can be reluctant to act promptly. For example, less than three hours after the Loma Prieta event, the Office of Emergency Services identified the center of major destruction as in or near Santa Cruz. Nevertheless, if one accepts the widely held view in the press and in emergency response circles, more than a day elapsed before those services received sufficient information on the disaster in Santa Cruz to dispatch rescue teams and equipment to the area.

Historical evidence concerning response to rare emergencies indicates that people require direct tangible evidence of a disaster before responding and that indirect scientific evidence, no matter how well founded, does not impel an action

response. The lesson is that human intervention in responding to an early warning will reduce the effectiveness of and may actually vitiate the entire system.

Current Early Warning Devices

Because major shaking generally begins with arrival of the S wave, the time between the arrival of the P and S waves can be used to provide some early warning. Most of the current systems noted earlier use this principle. At least two commercial products using the P-S wave arrival time difference have recently been marketed in California. Experience with them sheds light on the perceived benefits of such systems. One, manufactured by Quakeawake, is a simple battery-operated device consisting of a switch that closes when the unit is vibrated. It is intended to be mounted on a wall and emits a pulsed tone when triggered. Sensitivity is adjusted by tilting the unit. It has been sold for under $40 at popular retail outlets and came with a "survival guide." In advertising, the manufacturer claimed that the device will provide a warning of up to 20 or even 30 seconds.

Sales of this simple device in early 1989 were exceptional. The initial production run of 10,000 units quickly sold out, and TV stations had difficulty finding a sample to use for their news reports. The device was featured on many Los Angeles radio and TV news broadcasts, and the news media interviewed company representatives, customers, engineers, and seismologists. Whether this coverage was entirely in response to public interest or whether it helped to create this interest is uncertain. What is clear is that a large segment of the public perceived the device as beneficial. Interviewees said it would provide an additional margin of safety for their families, particularly their children. The timing of marketing this device was either well planned or quite fortuitous because it coincided with a number of minor earthquakes in the Los Angeles area.

The second device, actually a complete system, is marketed by Earthquake Safety Systems (ESS) of California. It uses the same type of seismic trigger as do strong motion accelerographs, including those in most nuclear power plants. This trigger has proven reliable over many years of use. The ESS system has modules and consists of separate components that perform different functions such as gas shutoff, water shutoff, electrical interrupt, sequential control, and earthquake alarm (early warning). The cost of an earthquake alarm package varies from $3,000 to $8,000, depending on the physical configuration of the triggers and the sophistication of the triggering algorithm.

An ESS system has been installed in the Los Angeles Music Center as a gas seismic shutoff system. A reported plan to upgrade this system will include an annunciator module for public earthquake warning in all three Music Center theaters. A social scientist was consulted about the content of the prerecorded message to be transmitted.

An ESS earthquake alarm system was installed in Grant High School, Los Angeles. When triggered by an earthquake, the system will broadcast a prerecorded duck-and-cover command to the campus. The intent of such a system is to minimize any delay in issuing such instructions that might arise from human indecision or the temporary absence of a teacher from the classroom. This particular installation received wide press coverage both locally and nationally.

Note that both Quakeawake and ESS give only minimum warning because they are triggered by the local vibration from a P wave. In addition, because of the large variation in S- to P-radiated energy, the sensitive trigger settings that are required can lead to false positive alarms. In this application, false positives are beneficial. Indeed, practice drills (i.e., deliberate false positives) are essential.

Based on the experience with these two products, it would appear that early warning is perceived as a benefit when tied to enhanced personal safety. It was not unusual for those interviewed to express the opinion that even a few seconds' advance warning would increase their children's chances of survival.

Response During Shaking

Real-time information provided during an emergency can influence the response to that emergency. If the seriousness of the emergency is known, the response can be measured accordingly. In an earthquake, knowing the ultimate level of shaking and the expected duration would provide an estimate of the expected damage. Just as the damage resulting from an earthquake with a 0.5 g peak acceleration differs from that of a 0.1 g earthquake, the damage from an earthquake with a 60-second duration will be quite different from one with a 6-second duration. Knowledge of the expected damage will certainly influence response to the event.

Real-time monitoring of earthquakes could provide continuously updated estimates of expected amplitude and duration of shaking. Responders would then have a basis for deciding among different response strategies. The response could be either automatic or through human intervention.

Real-time information could be used locally by those at risk and regionally by government agencies with an emergency response role. Information on the location and magnitude of an earthquake would speed the decision-making process on the deployment of emergency response resources. Enhanced real-time information concerning the distribution of ground shaking, along with maps showing the geographical distribution of different types of construction, could be used to identify regions of greatest potential damage and thereby refine further the deployment of emergency resources (Jones, 1985).

Rapid Postearthquake Information

Natural disasters in metropolitan areas pose special problems in emergency response. Some of the problems vary with the phenomenon involved. For example, devastating hurricanes are tracked for days by satellite and probed by specially equipped aircraft. Hurricane Hugo, for example, was probed, prodded, and studied extensively. Its progress across the Atlantic and toward the United States was monitored continuously, with almost a constant flow of information and probabilities of landfall issued to public officials and citizens alike. Thus, although property loss was substantial, loss of life was extremely low thanks to ample warning, preparation, and evacuation.

In contrast, earthquakes arrive virtually without warning, like being mugged from behind. For example, although we know that a large quake in the San Francisco Bay area is always a possibility, today's technology simply does not provide the type of earthquake warning that can be given for a major hurricane.

Full response to major earthquakes usually demands more resources than are immediately available. The greatest barrier to effective triage of these limited resources is the lack of timely, accurate information about the size and location of the earthquake and the area of greatest damage. As noted earlier, the first several hours of reporting of the Loma Prieta earthquake were characterized by the lack of accurate information about areas other than San Francisco itself and its major roadways.

A generally accepted technique for accurately estimating damage is dispassionate human reporting from helicopter or aircraft, but such reporting is limited to good weather and daylight. Thus, on October 17, San Francisco was just beginning to figure out how badly it might have been hurt when nightfall arrived. Severe earthquakes (e.g., $M=7$) can cause major damage in selected localities over hundreds of square miles far from the epicenter, as the 1985 Mexico City earthquake dramatically illustrated. Moreover, although aerial assessment can identify gross failures (e.g., dams, bridges), it cannot identify structures that have been dangerously weakened.

Other onsite reports are frequently inaccurate, inconsistent, sporadic, and too general to be of use to emergency response officials. In areas of greatest impact, communications may be so disrupted that observers cannot reach emergency response officials. Because of technical limitations, the existing seismic networks in California provide only modest information about possible magnitude and location.

A system that could provide high-quality real-time data on the intensity and location of the earthquake would have multiple benefits. It would:

- hasten the initial decision of both the state and the federal governments to activate the special catastrophic earthquake response plans,

- provide a more accurate preliminary damage estimate more quickly,
- allow a more rapid assessment of the possibility and timing of aftershocks that can pose serious additional safety hazards to both emergency response personnel and residents, and
- increase the efficiency and effectiveness of rescue operations, thereby mitigating damage and casualties as much as possible.

A difficult question for officials after a major earthquake is whether they had and used the best information that today's science can provide.

Tsunami Warning

Tsunamis are long-period (tens of minutes) ocean waves that are generated mostly by large submarine earthquakes. Only large earthquakes generate destructive tsunamis; but tsunamis are also generated by underwater volcanoes and perhaps by underwater landslides. Tsunamis that have devastated Hawaii were generated by earthquakes several thousands of kilometers away. The tsunami waves, which travel 700-800 km per hour, took several hours to traverse the Pacific Ocean to Hawaii, allowing a generous warning time. Indeed, much of our present tsunami warning system relies on the premise that tsunamis are generated in remote and distant regions of the Pacific. However, less distant earthquakes caused large tsunamis with run-up heights in excess of 20 meters that struck coastlines in 1868 (Hawaii), 1946 (Aleutian Islands), 1958 (Alaska), and 1964 (Alaska). Local tsunamis can be particularly dangerous not only because of their size but because they may strike within minutes of the causative earthquake. Although most of the coastal areas of the conterminous United States have not experienced historic devastating tsunamis, there is geologic evidence of large tsunamis from great subduction earthquakes in the Pacific Northwest (Heaton and Hartzell, 1987; Atwater 1987). Furthermore, it is difficult to preclude the possibility of damaging tsunamis along any U.S. coastal region.

Kanamori (1985) presented a methodology for determining tsunami size from near-field ground motions that occur within the first several minutes of large coastal earthquakes. Furthermore, reasonably precise predictions of local tsunami run-up heights are now feasible using complex models of sea waves in detailed models of sea floor bathymetry (Satake, 1987). However, on-scale measurements of long-period ground motions in the near-source region of large earthquakes must be available in real time for a local tsunami warning system.

Volcano Monitoring

On March 20, 1980, the regional seismic network operated by the University of Washington detected small earthquakes beneath usually quiet Mount St. Helens. Over the next two months, seismic activity increased dramatically as the volcano experienced several small phreatic (steam-blast) eruptions and the flank of the volcano bulged. Precursory activity was monitored carefully, a large area was evacuated, and many lives were saved from the catastrophic eruption of May 20. Monitoring seismicity in the region was a key tool for the prediction of numerous other eruptions over the next several years (Swanson *et al.*, 1983). Seismic monitoring has also been a key tool in the prediction of numerous eruptions in Hawaii (Klein, 1984). Smith and Luedke (1984) estimate that there are approximately 75 volcanoes in 11 western states of the conterminous United States that have potential for eruptions. In addition, 33 potentially active volcanoes are on the Alaska peninsula, 40 in the Aleutian Island chain, and 6 in the Hawaiian Islands (Simkin and Siebert, 1984).

Large explosive eruptions may or may not be preceded by significant periods of precursory eruptive activity. Simkin and Siebert (1984) report that of 205 of the largest documented eruptions, only 92 occurred within a day of the onset of eruptive activity. However, most (if not all) great volcanic eruptions are marked by significant seismic activity. For example, no precursory eruptions were reported for the 1912 eruption of Katmai (Alaska), the largest volcanic eruption of this century. But earthquake activity was noted for several days before the main eruption (Bullard, 1962). Thus, the monitoring of seismic activity is of vital importance for volcano prediction. This monitoring would require relatively dense seismic networks in the western United States, Alaska, and Hawaii.

Harmonic tremor, or volcanic tremor, occurs during eruptions and is characterized by a nearly continuous oscillation of the ground. The range of amplitudes of ground motion during harmonic tremor is large. Because of the unusual nature of the seismic source for harmonic tremor, this phenomenon is best studied with three-component broad-band instrumentation. It is important to monitor seismicity in volcanic regions in near real time. When visibility is limited (as it often is on large volcanoes), seismic monitoring can be the main or the only way to identify eruptions that may trigger dangerous lahars (mud flows caused by the rapid melting of snow and ice), as occurred with tragic results in 1985 at Colombia's Ruiz volcano, killing more than 20,000 people. In addition, even moderate size eruptions can send ash into the atmosphere that can be a serious hazard for aircraft.

Volcano monitoring is already an important task of some regional seismic networks, but to be effective and to analyze seismicity in real time, these networks should be upgraded to include three-component high-dynamic-range seismometers.

3
DEPLOYMENT

In an area of high seismicity, concepts for deployment of a monitoring system depend on whether the source is a known dangerous fault (e.g., the San Andreas) or a hitherto unknown fault (e.g., some of those concealed by young sediments in the Los Angeles Basin). In areas less prone to seismic activity (e.g., east of the Rocky Mountains), a regional array of closely spaced instruments is probably not feasible. Here a "fortress" around an essential facility may be the practical answer.

Deployment Along a Targeted Fault

A possible warning system for the section of the San Andreas fault near Los Angeles is shown in Figure 2. The sensors are located along the fault approximately 10 km apart (Holden *et al.*, 1989).

The warning that this system could provide for an M = 7.8 earthquake originating on the Coachella segment of the fault and growing northward is illustrated in Figure 3. The heavy straight lines represent the surface fault rupture. The heavy oval represents the Modified Mercalli Intensity VIII[1] from the USGS model of Evernden; the dashed line indicates the distance from the fault at which this intensity was observed in 1906 in San Francisco in the M = 8.3 quake. The concentric arcs, radiating from the earthquake epicenter, indicate the amount of warning time available at different distances from the epicenter. As shown, warning times for the Los Angeles area range from about 50 seconds in Riverside and San Bernardino to nearly 90 seconds in the northern San Fernando Valley.

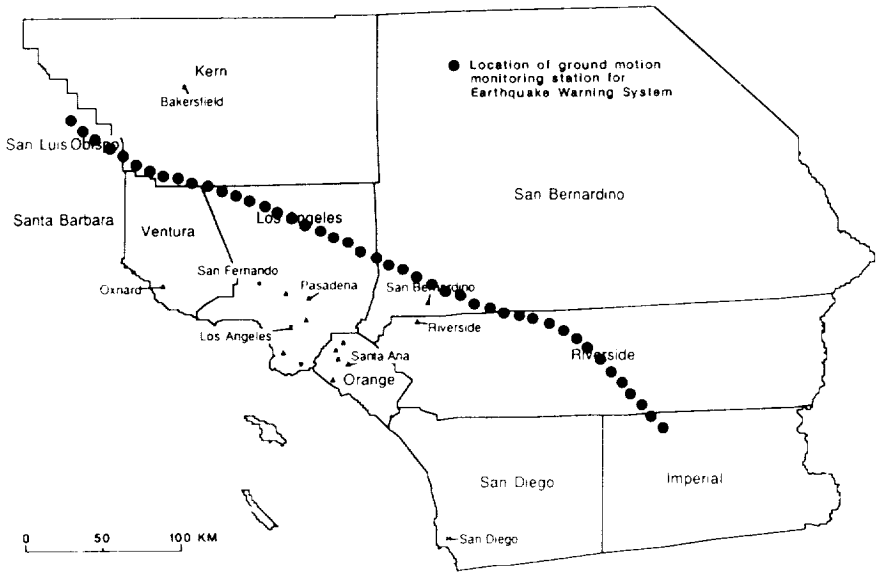

FIGURE 2. Schematic of sensor locations (10 km spacing) for an earthquake warning system to monitor the southernmost San Andreas Fault (from Holden *et al.*, 1989).

Seismic Area, Source Unknown

A system of a dense array of sensors (see Figure 4) is preferred when the source of the earthquake can be on an unknown fault or on one of many known faults (Holden *et al.*, 1989). The figure shows one possible station distribution for the Los Angeles area. The station spacing of 10 km would require more than 100 stations.

In any such system, there is a trade-off between cost and speed. For example, a 10-km spacing would have a basic overhead time (the time required after the origin time for the S-wave to trigger two or more sensors, assuming a source depth of 12 km) of about 5 seconds. Less expensive systems with sensor spacing of 20 km would have basic overhead times of 7-10 seconds. If the extra 2-5 seconds is insignificant compared with data processing time, then the wider spacing (cheaper system) would be adequate. Such a system would have provided only about 5 seconds of warning of the Whittier Narrows earthquake to users who

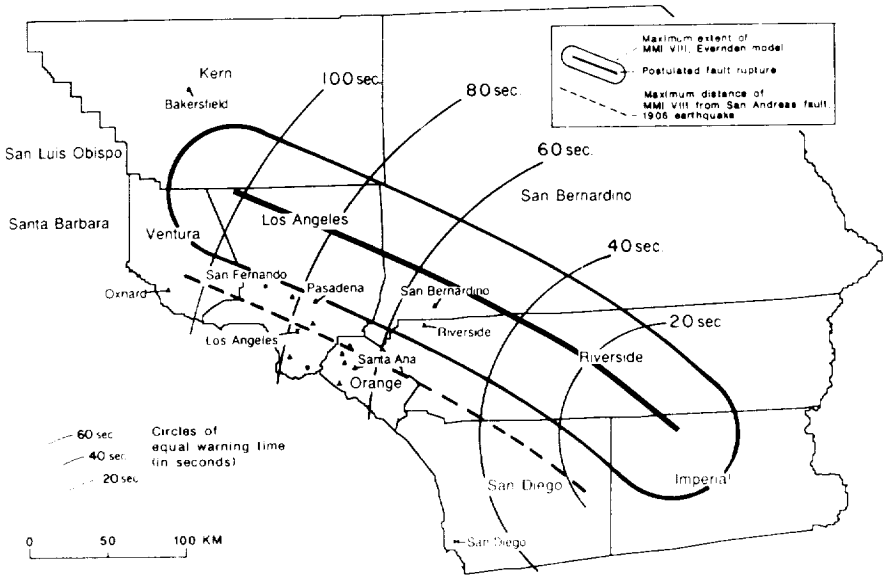

FIGURE 3. Postulated M=7.8 earthquake on the Mojave-Coachella segments of the San Andreas Fault (after Holden *et al.*, 1989).

experienced intensity VII shaking. Thus, such a system might not provide useful warnings for earthquakes with magnitudes less than 6.

An alternate design that would trigger the sensors on the P wave would require only about 2 seconds to trigger sensors on two or more stations 10 km apart. However, warnings based on P-wave triggers are more prone to false alarms—in particular, to alarms of earthquakes that do not cause damage. Nevertheless, a local P-wave trigger system may be the most economical for users who need only a short warning time. Note that this source-unknown configuration also is the sensor geometry needed for the immediate postearthquake information (RTEM) system. The sensors, to be installed as dictated by the local geology, would indicate the severity of shaking due to an earthquake, even one outside the net. Emergency services personnel would know almost immediately after the shaking which facilities and areas were likely to require their services. After a major earthquake, when facilities will be badly strained, this information will allow more effective mobilization than is possible today.

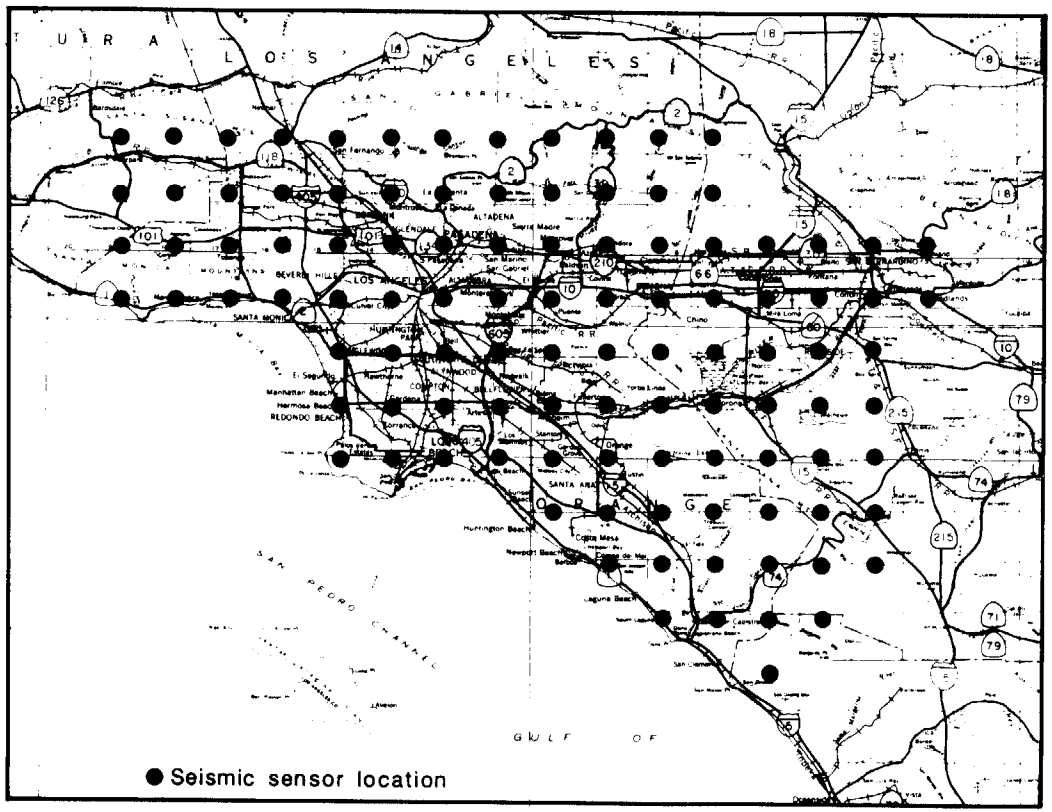

FIGURE 4. Possible monitoring station distribution for a Los Angeles regional warning system (after Holden *et al.*, 1989).

Areas of Low Seismic Frequency

In many areas in the United States, especially in the central-eastern states, the location and geometry of seismogenic structures are not well defined. In these areas it is not practical to have dense networks to monitor specific faults. The National Seismic Network, currently deployed by the USGS, will have an adequate coverage for monitoring of larger earthquakes. The station spacing of the national network in the central-eastern states ranges from 200 to 700 km. The current design of the network includes a semireal-time data retrieval system through satellite telemetry. It would be desirable to add real-time capability so that the broadband waveform data can be retrieved in real time. Waveform data are critical to obtaining source parameters necessary for real-time monitoring from a relatively sparse network.

If a specific structure is to be monitored, a few stations should be added around the target structure. Studies in other areas suggest that if waveform data are available, key source parameters such as the mechanism, seismic moment, and rupture directivity can be determined from a relatively small number of stations.

Note

1. The Mercalli Intensity Scale is based on the amount of damage at any given locality. The numbers, ranging from I to XII, therefore vary with distance from the epicenter and with the local geology.

4
TECHNICAL FEASIBILITY

Advances during the past several years in computer speed and communications (particularly by satellite) have made rapid data collection and processing technically feasible (Heaton, 1985). The attention of a number of seismologists to algorithm development has demonstrated that warning is possible. Research continues in improving the reliability of algorithms and reducing overhead time.

Data Collection

Some system configurations and algorithms require only relatively simple sensors such as force-balance accelerometers. (The cost estimate below is predicated on this type of sensor.) The relatively narrow bandwidth and limited dynamic range are sufficient for detecting the level (peak ground acceleration or other high-frequency parameter) of ground shaking at a site and issuing an alert.

However, because strong motion is relatively infrequent at any given site, testing of sensor operation would be difficult until the event itself. Moreover, the limited bandwidth may restrict the amount of long-period information available during even large earthquakes. For these reasons, high dynamic range, wide bandwidth sensors are desirable despite the greater cost.

Standard techniques of data transmission (e.g., telephone, radio, microwave) are vulnerable to strong shaking (Given, 1989). To provide complete information during the strongest events, data transmission would have to be hardened against damage from shaking (or ground failure). Because of the high data rates required for continuous data transmission, both analog and continuous digital systems may be prohibitively expensive. Costs could be reduced by transmission of selected or preprocessed data, which would significantly reduce the bandwidth requirement.

Another alternative is transmission by satellite, which would reduce the vulnerability of the communication links.

Data Processing

Real-time analysis of signals must: (1) detect signals of potential interests, (2) use some algorithm (expert system) to locate and estimate the size of detected events and distinguish potentially damaging events, (3) calculate the areas that could be strongly affected by the shaking, and (4) initiate communications to warn, alert, and/or inform appropriate users. The overhead time can be cut in a number of ways. For example, initial alerts could be issued based on information from a few stations and without a good epicentral fix. Those alerts could be updated as more data become available. However, more information is required to distinguish potentially damaging events and to estimate the area of probable strong shaking. A rapid estimate of earthquake size will help to reduce system overhead time, and an estimate of rupture direction and length is needed to estimate the affected area.

A number of algorithms for estimating earthquake size have been published (Toksöz *et al.*, 1987, 1990a, 1990b). Algorithms for estimating the distribution of damage (intensity) are available, and they could easily be incorporated into the real-time processing system. New algorithms using expert-system techniques and pattern recognition are needed for a general RTEM system.

During the past decade, several data processing systems have been developed to give real-time location within minutes. For example, at Menlo Park, the USGS central and northern California seismic network routinely locates earthquakes within minutes, using three different computers that continuously analyze 400 seismic channels to detect the arrival of P waves. This system is commonly referred to as a real-time processor (RTP).

The Southern California Seismic Network also has an RTP that analyzes 64 channels of data. When seismic arrivals are detected on at least 4 stations, an event is declared and the arrival times and amplitudes are sent to other computers for further analysis. Earthquake locations are generally available within 5 minutes, and a system of physical alarms can be activated by computer mail and radio paging systems. Current plans are to construct a new generation of RTP devices that will handle all 260 channels in southern California (Bakun *et al.*, 1986). This development will make the locations more reliable and should allow better magnitude determination by using low-gain information. In Hawaii, an 84-

station RTP device has been developed independently by Carl Johnson and Thomas English at the Hawaiian Volcano Observatory. This RTP is an integral piece of the seismic data analysis system, and locations are available in as few as 15 seconds. New and improved versions of these systems are being developed.

Data and Information Dissemination

Once the real-time data are assembled and processed, the method of dissemination will depend on the needs of the user. For government agencies, the information could be supplied by direct communications links such as satellite or microwave. The number of these agencies is sufficiently small that there would be little difficulty in designing special communications links for their use.

Dissemination to the public at large presents a greater challenge. The information could be provided without charge over existing communications networks such as radio, TV, and the telephone, or it could be provided by paid subscription. One example of a rapid dissemination system is the Public Information and Notification System (PINS).[1] Alternative systems could readily be designed using current technology.

A general early warning and real-time information system must be relatively simple. Information provided might include a continuously updated estimate of the time of the event, its location, its magnitude, and its duration. Local processors could be built to convert this information into estimates of the level of local shaking. An aerially deployed system of sensors with a true real-time capability can also be used for the rapid development of a map of the intensity of ground shaking. Such information could be disseminated by direct satellite or other communication link. The necessary software and hardware are well within present capabilities.

News bureaus, along with local and network news organizations, should be included in the system and trained in its use. This would help to reduce the substantial amount of inaccurate information given to the public in the early hours after a major quake.

System Costs

The costs of implementing RTEM networks would vary with the capabilities of existing networks and the specific data and analysis requirements. A fully

instrumented, totally new RTEM would be expensive. However, in places such as southern California, improving the real-time capabilities of the extensive existing networks would be relatively inexpensive and would be a major step forward. Current California and RTP algorithms could be upgraded to provide initial location and rough magnitude estimates within 3 minutes for approximately $30,000. As the RTP output algorithms become faster and more reliable, operators might consider providing the RTP directly to certain users, such as emergency response agencies. Because the California systems already contain "beeper" connections, extension to emergency response users would be quite inexpensive. In other parts of the continental United States, the addition of an RTP to existing regional networks would be more costly, perhaps $50,000-75,000 per network.[2] There would, of course, be substantial costs to harden the telemetry links.

The upgrades and station density required for sophisticated real-time applications in areas such as the Los Angeles Basin are probably not feasible for most other parts of the continental United States. But some real-time elements can be incorporated into networks with more sparse station spacing. The National Seismic Network plans do not currently include real-time operations as discussed in this report.

Because possible systems and their capabilities vary widely, the panel found it impractical to detail the costs of installing and operating new systems. Estimates for some systems do exist, for example, in the California report (Holden *et al.*, 1989). But we emphasize that estimates of capital and operating costs for RTEMs are very sensitive to the assumptions incorporated into system design. The geographic area covered and station density decisions are affected by the types of data and their anticipated uses. Data transmission options may be limited by the need for continuous data flow during strong shaking. The different requirements and options for data processing (including sample rate, number of stations, amount of preprocessing, timing requirements, and hardening/redundancy) will determine the type of central processing facility required.

Management Issues

Because the concept of real-time earthquake warning is new, a means of improving the methodology should be built into any system that is installed. A real-time system will also provide high-quality waveform data useful for detailed studies of earthquake physics and structural engineering. Thus, close interaction

among the research community, operators, and emergency services officials is essential. One possible mechanism to promote such interaction might be an advisory committee of users and operators to provide guidance for stable and effective operation and to ensure ongoing evaluation and improvement of the monitoring system.

A management system must be developed that enables users to acquire data quickly and easily. Because the National Seismic Network will have semireal-time telemetry capability (Massè and Buland, 1987), any real-time monitoring system should be interfaced with its data archival system. In addition, we recommend adding real-time telemetry to the national network.

If the data are archived as a part of the national network data base, the proposed management structure of the national network will be effective for data distribution.

Notes

1. PINS is a refinement of the Automatic Radio Information (ARI) system developed by Blaupunkt in the early 1970s on behalf of the German Government and the German Automobile Club. The ARI system has been used to disseminate traffic status information in several European countries and was introduced in North America in 1982. PINS I is an enhancement of the ARI technology that was developed shortly after the Three Mile Island accident in 1979. It uses a 57 kilohertz subcarrier on radio broadcasts as a mechanism for transferring messages and information control characters within the system. The PINS I system can quickly "take control" of all media (e.g., radio, TV, cable) to which it is attached to provide emergency messages. A further enhancement, PINS II, adds another special subcarrier to the broadcast signal, which allows greater flexibility and selectivity of the alerting system as well as greater operational security. PINS II can transmit digital data over the subcarrier to selected receivers such as emergency response agencies. PINS II also operates an emergency home receiver. Advantages of a system like PINS are the built-in redundancy and reliability and the small capital costs to the end user. (Home receivers are currently priced at $40 each, industrial receivers at $300 each.) An additional advantage of PINS is its multihazard possibilities. Once the configuration

is developed, the warning messages can originate from a variety of localities, and the messages can warn on a variety of hazards. Disadvantages of this system are the large up-front costs (approximately $2-5 million for coverage, both digital and voice, of the Los Angeles Basin) and the overhead time to pass a message through the system (approximately 5 seconds).

2. As RTP is not yet an "off-the-shelf" item, these costs are only an educated guess.

5
NONTECHNICAL CONSIDERATIONS

System Evaluation

Technical feasibility is irrelevant unless there is public interest in spending money for the system and using it appropriately. Evaluating a system that has yet to come into being is a difficult, if not futile, task, particularly if that system is intended to produce a hitherto unavailable product or function. The conventional method of evaluation is a market survey in which a cross section of users is asked whether they could or would use the product and, if so, what they would be willing to pay for it. *The method is unreliable.* Innumerable new technologies have been turned down initially by potential users. Cases in point are the rejection of the telephone in favor of messenger boys by the British Post Office (1876), the rejection of the telegraph by the U.S. Post Office (1845), and the abandonment (albeit temporary) of monoplanes and the continued reliance on biplanes by the French military (1915). More recent examples include initial rejections of computers, transistors, and television.

On the reverse side, there have been instances in which a product was introduced after a highly favorable market survey only to have the public reject it later (e.g., the "New Coke").

Many successful products or services have been introduced after their proponents have correctly evaluated their potential use or demand and have made the product or service available despite initial indifference or opposition by prospective users.

Despite their deficiencies, market surveys are widely used, probably for lack of a good substitute. But any interpretation of a market survey should take into account the unreliability of the method.

Cost-Benefit Analysis

Cost estimates of physical damage are straightforward and relatively simple to make. Potential benefits of any new system are hard to quantify (Mishan, 1976). For a cost-benefit analysis of a system such as the RTEM, account has to be taken of the cost of lives *potentially lost or saved* by that system. Our ethical systems abhor equating the value of a human life with any sum of money. Practical considerations in everyday situations, nevertheless, require assignment of monetary value to human life.

In actual practice, the value set on a human life ranges widely (Zeckhauser, 1975; Rhoads, 1978; Linneroth, 1979). One commonly used method is the discounted future earnings approach. It takes the average age of death from a particular type of decedent and computes expected future income had the individual lived. Typical values range from $100,000 to $400,000 (Rhoads, 1978).

Within the recent past, the consensus of the value of the life of a named accident victim has been up to $1 million in damage awards in U.S. courts. Such awards are rarely less than $100,000 or more than $10 million.

On the other hand, a "generic" life, by which is meant a life that may potentially be saved in some future accident or catastrophe, typically (but not always) has far less value. For example, the installation of a traffic signal involves a one-time cost of about $20,000. Throughout the nation, signals are installed at intersections not because of traffic considerations but because of popular demand. Such a demand most commonly arises when several deaths occurred within a period of a few years—that is, a capital expenditure of about $20,000 was made to avoid a loss of one life per year. The cost of installing air bags in cars is estimated at $10,000-$20,000 per life saved per year; yet the installation of air bags has been slow.

Assuming a 20-year useful life for a traffic signal and 10 years for a car, one might conclude that a generic life is worth less than $1,000. When the public is in the habit of grossly underestimating or overestimating a hazard to life, a generic life can differ from this figure by several orders of magnitude.

Alternative Choices

Are there alternatives to a real-time earthquake sensing and analyzing network for assessing the location and extent of a major shock in time for optimum

disaster response to take place?

With existing seismograph systems, areas of major damage are identified most quickly by physical observation on the ground or by overflight from slow, low-flying aircraft, preferably helicopters. Direct reporting from observers in the damaged areas is spotty because access to functioning communication may be severely restricted. Such unreliability escalates with increasing severity of ground motion—the worse the damage, the less reliable the reporting.

We believe that any suggested alternative to the RTEM system would interpose a substantial time delay in disaster assessment. The delay is composed of the time needed for reporting the existence, magnitude, and location of the event; the time needed to activate the surveillance system (regardless of its nature); and the time required to search for and reach the presumed areas of major intensity.

A real-time system, particularly if it consists of an areawide grid of instruments, would make this information available within minutes (perhaps seconds), so that normal traffic into the damaged area by pipeline, rail, highway, and air could be shut off or diverted and emergency services properly directed in the shortest possible time.

Public Perceptions

Public acceptance of precautions or preparations for potential hazards commonly have little or no relationship to the objective evaluation of risk (Raiffa, 1982; National Research Council, 1989a). Particularly inconsistent is the popular response to a danger of low subjective probability. Even in an area of relatively frequent earthquakes, such as California, any one individual residing in a specific locality will probably live his or her entire adult life without experiencing a personal injury or structural damage to a home as a consequence of an earthquake.

In 1985, Field Research asked 503 California residents how likely they thought it was for a major earthquake to occur in their area. Sixty-two percent said they believed it was very, or extremely, likely. But 90 percent of those same people were personally worried only a little or not at all, and 79 percent thought their chances for survival in a major quake were good or excellent. Whether these percentages hold in 1990 is a moot question.

Until quite recently, earthquake risk to any one individual has been viewed as so remote that aesthetics or a minor monetary benefit outweighed the potential danger. For example, during the February 9, 1971, quake in San Fernando Valley, a great deal of the structural damage to post-1933 residential construction

occurred in houses that had received variances to the building code to provide a "more pleasing" appearance to the garage door. When no damaging earthquake occurs for years, the perception of risk diminishes.

The public has no good basis for evaluating the competence of a given scientist or the validity of his/her public statements (Raiffa *et al.*, 1982). Thus, response to the conclusions of scientists tends to reflect the drama and style of the publication of those conclusions rather than their objective scientific merit. Legislation or other public response to earthquake hazards is vastly more likely to occur immediately following a destructive quake than when the historical record shows that a major earthquake can reasonably be anticipated within the next decade or two. Such recommendations as those contained in this report will therefore usually engender negligible public support unless there has been a recent, destructive quake.

Universal Studio's theme park in southern California recently opened an exhibit that sensationally and realistically simulates the destructive effects of an $M = 8.3$ earthquake. It remains to be seen whether this attraction will move the general public toward acceptance of measures such as the real-time prediction system to aid recovery from the effects of a major shock.

Life and Safety

In addition to individual actions to enhance personal safety, such as diving under a desk, some that can be taken to protect both life and property, such as shutting off fuel supplies to industrial or commercial installations to avoid fire. Other potentially hazardous activities that can be shut down are high-speed trains, industrial conveyors, and the like. Unfortunately, shutting off such activities entails severe financial penalties in the event of a false positive. Certainly, some false positives will occur over the 50- to 100-year or more interval between major quakes in any given area.

In contrast, automatic alarm systems in schools or other institutions will not be adversely affected by false positives. Indeed, periodic drills (i.e., deliberate false positives) are required to make the system effective. Even a few seconds of warning will enable students to take effective measures to reduce deaths or injuries.

As stated elsewhere, the monitoring system can also be used as a reporting system and can prevent injuries or save lives by diverting people and hazardous materials from severely damaged areas and by making emergency services more promptly available.

Facilities: Automatic Versus Manual

To be most effective, the response to a real-time warning must be automatic. A system based on human intervention would require a permanent staff of competent, trained monitors on a 24-hour uninterrupted alert status. People with the competence to make an intelligent decision on whether to act on an alarm are not likely to accept a position that would entail months or even years of inactivity. And if monitor staffs had other duties and were only alerted by the alarm, the inevitable delay would consume much (if not all) of the advance warning time.

Any system that has to operate reliably once every 30-50 or more years must be exercised frequently. All working parts and the entire system have to be tested. Even more important, all potentially affected personnel must become accustomed to the functioning of the system. An ever-present danger of automatic hazard reduction systems, particularly those rarely activated, is that personnel will tend to override the automatic system manually, as happened at Three Mile Island. There, in 2.5 hours, the staff manually overrode the automatic shutdown three times despite increasing indications of reactor malfunctions and despite prior instruction on operation of the automatic system.

Large national defense establishments commonly have some sort of local seismic monitoring system. But a large real-time monitoring system will be a useful backup, if not a replacement, for the primary sources of information. The precautionary measures against earthquake hazards in defense establishments mainly involve the storage or transport of hazardous materials. Both military and civilian transport and storage of hazardous materials are viewed by the public with considerable alarm. RTEM systems that may give a few seconds' warning prior to a destructive earthquake will go a long way to allay fears.

False Alarms

An important socioeconomic issue is the frequency and cost of false alarms. Without several lifetimes of experience with, and the fine-tuning of, the system, false outputs will inevitably occur. System malfunctions and accidents will occur, maintenance personnel will make errors, and institutional memories will be lost. Experience with large systems has shown that only actual events can adequately test those systems and that simulations and synthetic modeling cannot completely anticipate reality.

The CDMG study (Holden *et al.*, 1989) estimated the probable frequency of false alarms in the United States by reviewing the performance of the automatic warning system of Japan Railways. During its first 20 years of operation, the Japanese system stopped the Bullet Train 100 times, an average of 5 times per year. In all 100 cases, the trigger was an earthquake. (The Japanese system has fewer than one false alarm per year. Most of these result not from earthquakes but from a failure in the electronics or sensors.) In two of the shutdowns due to real quakes the tracks were actually bent, but in neither case were they bent enough to be dangerous. The Japanese have recently adjusted their triggering algorithm to reduce the number of real alarms from 5 to 2 per year.

Because the seismicity of California is about one-tenth that of Japan, a simple trigger could be expected to produce one-tenth the number of alarms in Japan, about one alarm per year. The rate of Japanese false alarms caused by instrument failure (about one per year) could be expected in a system here. This false alarm rate could be much reduced if nearly simultaneous triggers of two adjacent sensors were required to produce an alarm.

The CDMG study evaluated the effect of the cost of a false alarm on the feasibility of an earthquake warning system. False alarm costs include the loss of production time when a factory's operations are suspended and personal injuries caused by response to a warning. The study concluded that at this time, there is no reliable measure of the actual cost of a false alarm. Table 6.2 of the study shows what the savings produced by an earthquake warning system would have to be (to be cost-effective), assuming three different false alarm costs and three different false alarm rates. The table shows that the necessary savings vary by a factor of six for these different rates and costs.

The false alarm rate has far greater significance for the acceptability of an earthquake warning system in California than is reflected in these figures. According to the CDMG study (see section VIII G), many potential users of an earthquake warning system are so skeptical of its reliability that they are unwilling to have their operations respond automatically (i.e., without human intervention). The reluctance of potential users to rely on a fully automated system is at least partly responsible for the conclusion of the CDMG study that such a system cannot be justified (at this time) on a cost-benefit basis. (As we state elsewhere, however, given the short time available and the common human responses—disbelief, delay, and even overriding of automated systems—we consider an automated response essential.)

Although some false alarms must be anticipated, we note that different false alarms can have quite different effects. For example, a false *negative*, that is, a

major earthquake that is not reported by the system, will vitiate the entire purpose of the system. Not only will the steps not be taken to mitigate damage and loss of life, but also the failure will add to the normal hesitation in effecting precautionary steps that would be enhanced for future warnings.

On the contrary, a false *positive*, that is, reporting an earthquake that did not occur or reporting a minor one as destructive, will have a major effect on installations whose response is costly, but it will have little or no effect on the general public. (The public, after all, is accustomed to false alarms of fires, hurricanes, and other natural hazards.)

False negatives can be reduced by redundancy and error-correcting exercises. Reduction of false positives will require continued research for the foreseeable future. Our conclusion is that the triggering threshold for the system should be biased to make it extremely unlikely that a major event will not be reported.

Liability

If an RTEM system is established, realistic legislation needs to be enacted concerning compensation of those who may be damaged by their reliance on the system (Holden *et al.*, 1989). No private organization that would operate all or part of the system or supply equipment could accept a liability that is effectively unlimited. If a government agency installs or operates the system, it can rely on the doctrine of sovereign immunity to protect itself, and it could extend that immunity to governmental employees, agents, or suppliers. This protection would not extend to the general public.

6
OTHER REPORTS

Two recent reports are pertinent to this study. First is the report of the California Department of Conservation, Division of Mines and Geology, which conducted a feasibility study of an Earthquake Warning System (EWS) and released the report to the California Legislature early in 1989 (Holden *et al.*, 1989).

This study was mandated to explore only a narrow concept of the EWS—that is, the utilization of a 1- to 120-second early warning by a limited number of industries and sectors of society. Within this context the report was well documented and presented a great deal of pertinent information. Indeed, our report has relied heavily on both its information and language.

The CDMG conducted four surveys to determine the needs of potential users. Surveys of 80 large companies and government agencies and 75 smaller firms in the vicinity of Whittier were conducted. In addition, an earthquake engineering firm analyzed its damage data base to determine whether warnings could have mitigated damage from previous earthquakes worldwide.

Although definite interest was expressed by many of the responding companies, they were not, in general, able to be specific about uses of such a system or its potential dollar benefits. Warning times of 1 minute or longer were desired for most uses (70 percent) that were specified. Many expressed concern over the reliability of the system and the potential cost and damage of false positive alarms; in fact, more respondents could cite a cost in dollars for a false alarm than could cite an estimated savings from early warning.

The California report concludes that no compelling evidence was collected to indicate that the EWS could be justified solely on a cost-benefit basis.

For the California report to be properly used and interpreted, its context and limitations should be clearly understood.

1. As noted above, the mandate under which the California report was prepared was more narrowly focused than the charge to this panel. Consequently, some of the potential benefits of an EWS as we see them were not considered fully in its evaluation.

2. The 15-county survey was based on an intentionally selective sample of 168 large users (88 of whom later chose not to participate) plus 78 small users in the Whittier area. This number may not be a sufficiently large sample of potential users on which to generalize.

3. A large percentage of the respondents did not answer the question about user benefits of such a system. Because these selected companies were thought to be among the more sophisticated and knowledgeable, the responses suggest that the level of knowledge and awareness from a full random sample of potential users would be even lower and the data less meaningful. Most potential users are apparently unable to evaluate the benefits of an EWS at this time.

4. The study's mandate to evaluate the cost-benefits of an EWS restricted an evaluation of the value to earthquake research. One value of a real-time EWS would be the amount of improved data provided to seismologists and engineers. These data are essential in improving real-time alerts.

5. Although Table 3.1 of the report shows that the survey includes some hospitals and emergency response organizations, the discussion does not describe the benefits to the disaster and emergency response community. Mitigation of earthquake damage—lives, injuries, and damage to structure—is linked to the speed and targeting of emergency resources and would be a major benefit of the system. Putting a dollar value on this type of benefit is difficult at best.

6. The study was not mandated to explore issues of information, awareness, and planning on the part of the general public, perceptions that the panel believes to be important in assessing the social cost-benefits of an EWS.

A few specific comments follow. In discussing the economic evaluation of the EWS, the CDMG report states: "The estimated savings and false alarm cost data from the survey results contain too much variability to be used in a rigorous cost-benefit analysis" (page 62). The report also acknowledges the extreme difficulty in trying to assess and assign economic value to an important potential benefit of early warning—the reduction of casualties.

The report cites the experience from the 1983 Coalinga earthquake in which "more injuries occurred to those who exited buildings than to those who remained inside." It concludes: "An EWS used for such purposes may, in fact, result in greater casualties." This situation is clearly a problem of education of the public.

More important, however, it may be an indicator that a short warning of 15 seconds or fewer, which permits the public time to "duck," could be of greater value in casualty reduction than a warning of 2 minutes.

In summary, we agree with the CDMG; the data cited in its report are not conclusive for either supporting or rejecting the deployment of an EWS system on the basis of the financial cost-benefit alone. But we also conclude that a broader concept of an EWS, such as considered in this report, can lead to a different conclusion.

The second pertinent report is *Estimating Losses from Future Earthquakes* (National Research Council, 1989b). This report focuses on loss estimation based on deterministic and probabilistic modeling. It concludes that such modeling for "planning disaster response and financial assistance" has limited practical value owing to the uncertainty factors of 2 to 10. Throughout the report, the inadequacies of the existing data base are cited as major limitations to existing modeling attempts and their resultant accuracy. We concur emphatically. However, the RTEM visualized by this panel would have as one of its benefits the collection and dissemination of just those data that would help the theoretical modeling crucial in planning disaster response.

7
CONCLUSIONS AND RECOMMENDATION

Everyone would like to have the same warning time for a major earthquake as the East Coast had for Hurricane Hugo. But the source of earthquakes is in a realm of our environment that does not yield easily to direct observation. We cannot fly an airplane into the eye of an earthquake or take pictures of it with a satellite. We do not have all the answers on why earthquakes occur, and we do not know where all of the faults lie. Even in well-studied parts of California, earthquakes sometimes originate on concealed faults that were undetected prior to the quake.

Yet the study of earthquakes has come a long way in the past 50 years, and a number of measures to reduce the effects are possible. One of these is an RTEM system. Concerning such a system, the panel's conclusions are:

1. Recent advances in instrumentation, communications, and processing of information make an RTEM system technically feasible.
2. Tangible benefits to real-time seismic information systems include not only the early warnings for "duck and cover" and automated shutdowns but also the more effective deployment of emergency resources, the improved estimation of aftershock probabilities, and the higher-quality information that can further improve the detection/warning system.
3. Most real-time warning applications should be coupled eventually to automated responses. Further development and education are needed before implementing such responses.
4. Real-time seismic information systems would be an important addition to the plans for the National Earthquake and Hazard Reduction Program.
5. Small special-purpose real-time systems are already being established. If such special systems continue to evolve without coordination and guidance, they

will be too varied to be included in a network system of shared information. Consequently, the aggregate expenditure will not produce a system as effective or as comprehensive as the one visualized here.

6. A logical and economical first step to move to an integrated RTEM system is to expand and upgrade existing networks to include three-component high-dynamic-range seismometers. Prototype system designs built upon existing data and networks are the most efficient mechanisms to develop and gain experience with an RTEM system.

7. An RTEM system must have a strong research component. Particularly in sparse networks, estimation of damage potential requires more than the current knowledge about propagation. For early warning applications, the reduction of false positives requires more accurate vibration determination than is presently possible.

8. The National Seismic Network will be the major earthquake monitoring network east of the Rockies. Adding a capability for real-time output would enhance its value. Although California is the site of frequent seismic activity, the threat of a major quake is definitely not limited to California.

9. Integrated management systems are essential to ensure collection and dissemination of data.

Based on the above, we recommend the installation of a prototype system. Probably the most efficient course would be to upgrade one of the existing (California) networks. This would take advantage of an existing infrastructure and would then build on experience. During the initial phase, many companies will use the provided (multilevel) signals for demonstration or evaluation only. Moreover, the system should be associated with research and evaluation activities, working with the users, to improve system reliability and usefulness. The system should provide sufficient information that users can better decide their needed level of response.

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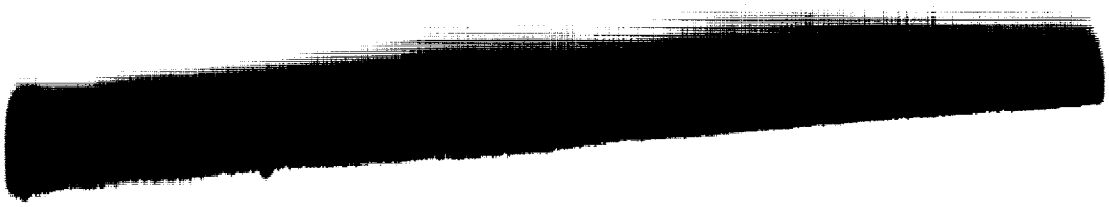
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