EARTHQUAKE EARLY-WARNING SYSTEMS: CURRENT STATUS AND PERSPECTIVES

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ABSTRACT

As increasing urbanization is taking place worldwide, earthquake hazards post strong threats to lives and properties for urban areas near major active faults on land or subduction zones offshore. Earthquake early-warning systems can be a useful tool for reducing earthquake hazards, if cities are favorably located with respect to earthquake sources and their citizens are properly trained to response to earthquake warning messages. The physical basis for earthquake early-warning systems is well understood, namely, destructive S- and surface waves travel at about half the speed of the P-waves, and seismic waves travel at much slower speed than signals transmitted by telephones or radios.

At least three countries have earthquake early-warning systems in operation: (1) Japan, (2) Mexico, and (3) Taiwan. These systems can provide a few seconds to several tens of seconds of warning for large earthquakes. With recent emphasis on real-time seismology, operators of many regional and local seismic networks are now upgrading their systems to reduce the time for issuing an earthquake notice from several minutes to under a minute, thus potentially making earthquake early-warning a technical possibility. More significantly, a properly upgraded seismic network can provide a shake map within minutes after a disastrous earthquake, so that loss estimation from an earthquake can be quickly assessed to aid disaster response and recovery.

At present, the Seismic Alert System (SAS) in Mexico City is the only system issuing earthquake warning directly to the public. As it is appropriated for the International IDNDR-Conference on Early Warning Systems for the Reduction of Natural Disasters (EWC'98), we will discuss the societal experience of this system during the past few years.

1. INTRODUCTION

The present technology in seismic instrumentation and telecommunications permits the implementation of a computerized system for earthquake early warning. Such a system is capable of providing from a few seconds to a few tens of seconds of warning before the arrival of strong ground shaking caused by a large earthquake. This timely information may be used (1) to minimize property damage and the loss of lives in metropolitan areas, and (2) for real-time loss estimation to aid emergency response and recovery. The purpose of this paper is to present a brief review of the advances in earthquake early-warning systems and to examine its current status and perspectives. As this paper is intended for a general audience, no technical details will be presented, but the interested readers can consult the extensive bibliographic references given at the end of the paper. Because the Seismic Alert System in Mexico City is the only system issuing earthquake warning to the public, we will discuss the societal experience of this system during the past few years.

In addition to this EWC'98 International Conference, four technical sessions on earthquake early warning systems were held in conjunction with the following international meetings:

- The XXI General Assembly of the International Union of Geodesy and Geophysics in Boulder, Colorado, USA (*see* Lee and Shin, 1995),
- The Eleventh World Conference on Earthquake Engineering in Acapulco, Mexico (*see* Lee and Espinosa-Aranda, 1996),
- The 29th General Assembly of the International Association of Seismology and Physics of the Earth's Interior in Thessaloniki, Greece (*see* Lee et al., 1997), and
- International IDNDR Conference on "Modern Preparation and Response Systems for Earthquake, Tsunami and Volcanic Hazards" in Santiago, Chile (*see* Instituto Geografico Militar de Chile, 1998).

The references cited above gave abstracts (and sometimes, extended summaries) of papers submitted. Complete papers for the Mexico session can be found in the Proceedings of the Eleventh World Conference on Earthquake Engineering on CD-ROMs.

In addition, several papers related to earthquake early warning were presented at the Union session on "Hazard Mitigation: Use of Real-Time Information" during the 1997 Fall Meeting of the American Geophysical Union in San Francisco, California, USA (*see* Ward and Cluff, 1997). A progress report on "Real-time Seismology and Earthquake Hazard Mitigation" was presented by Kanamori et al. (1997) in the popular scientific journal, Nature. References to technical details will also be given as we discuss the issues below.

An earthquake early-warning system can be constructed from systems for real-time monitoring. Such real-time systems have other applications, e.g., in tsunami warning and in monitoring volcanic eruptions. However, it is beyond the scope of this paper to discuss these topics.

2. SOME BACKGROUND INFORMATION

Cooper (1868) proposed the idea of an earthquake early-warning system for San Francisco, California, more than one hundred years ago. In the mid-nineteenth century, there were frequent earthquakes near Hollister, California, about 120 km southeast of San Francisco. Cooper proposed to set up seismic detectors near

Hollister and when an earthquake triggered them, an electric signal would be sent by telegraph to San Francisco. This signal would then ring a big bell in City Hall to warn citizens that an earthquake had occurred. At that time, scientists already knew that an electric signal travels much faster than seismic waves. Unfortunately, Cooper's scheme was never implemented. More than 100 years later, Heaton (1985) proposed a seismic computerized alert network for southern California, and Bakun et al. (1994) implemented an early warning system for aftershocks of the 1989 Loma Prieta earthquake using modern hardware in a scheme similar to Cooper's.

In the mid-1960's, China, Japan, USA, and USSR initiated extensive earthquake research programs. These programs emphasized earthquake prediction and some seismologists at that time were optimistic that earthquake prediction could be realized in 10 years. However, the ability to predict the time, place, and magnitude of an earthquake accurately remains elusive (U. S. National Research Council, 1991). More recently, Geller (1997) presented a critical review of earthquake prediction, and concluded that:

"Earthquake prediction research has been conducted for over 100 years with no obvious successes. Claims of breakthroughs have failed to withstand scrutiny. Extensive searches have failed to find reliable precursors."

It is now recognized that earthquake prediction is an extremely difficult problem to solve, because the earth is complex and we don't fully understand the earthquake generating process (Knopoff, 1996; Evans, 1997). Although earthquake prediction research is yet to attain its goal, increased funding from the 1960's has resulted in advances in many fronts in seismology, including the development of regional and local seismic networks (see for example, Lee and Stewart, 1981).

We cannot ignore the increasing economic and human loss due to earthquakes because of rapid urbanization around the world. For example, recent earthquakes such as, the January 17, 1994 shock in Northridge, California, and the January 17, 1995 shock in Kobe, Japan, caused about US$20 billion and US$100 billion in damage, respectively; and over 5,000 persons lost their lives in the Kobe earthquake. Therefore, in recent years some seismologists and earthquake engineers have turned their attention to developing and implementing systems that can provide early warning or rapid response to large earthquakes in order to minimize loss and to aid recovery.

3. PHYSICAL BASIS FOR EARTHQUAKE EARLY WARNING

The physical basis for earthquake early warning is simple: strong ground shaking is caused by shear (S) and the following surface waves (which travel at about half the speed of the primary (P) waves), and seismic waves travel much slower than electromagnetic signals transmitted by telephone or radio.

Figure 1 shows an example of a prototype system for earthquake early warning, which was implemented in Taiwan. Figure 1(A) is a map showing the geographic location of the Hualien Network and Taipei, capital of Taiwan. Figure 1(B) shows accelerograms recorded in Hualien and in Taipei from an earthquake marked by "*" in Figure 1(A). The amplitude of the Taipei accelerogram has been magnified 6 times relative to that of the Hualien accelerogram. The time scale is shown at the top of Figure 1(B). "O" stands for the origin of the earthquake, "P" for P-wave onset, and "S" for S-wave onset. In Hualien, the P-wave arrived in about 3 seconds, and the S-wave arrived in about 5 seconds after the occurrence of the earthquake. On the other hand, in Taipei (about 120 km from Hualien) the P-wave arrived in about 12 seconds, and the S-wave arrived in about 21 seconds. In both cases, the amplitude of the S-wave is much larger than that of P-wave. Since the Hualien Network is capable of locating an earthquake and estimating its magnitude in about 10 seconds, a warning signal sent to Taipei by telephone circuit arrives just before the P-wave, and about 11 seconds before the larger S-wave.

To illustrate the above observation in general, we plot the travel time for P-wave and S-wave versus distance in Figure 1(C). We make the following assumptions of a typical destructive earthquake: (1) focal depth at 20 km, (2) P-wave velocity at 8 km/sec, and (3) S-wave velocity at 4.5 km/sec. If an earthquake is located 100 km away from a city, the P-wave arrives at the city in about 13 seconds, and the S-waves in about 22 seconds according to Figure 1(C). If we deploy a dense seismic network in the earthquake source area that is capable of locating and determining the size of the event in about 10 seconds, we will have about 3 seconds to issue a warning before the P-wave arrives, and about 12 seconds before the more destructive S-waves and surface waves arrive at the city. Here, we have assumed that it takes very little time to send a signal from a seismic network to the city by electromagnetic waves (e.g., telephone circuit) at nearly the speed of light (300,000 km/sec).

From Figure 1(C), it is clear that the above strategy may work for earthquakes located about 60 km or more away from a city. For earthquakes at shorter distances (say, 20 to 60 km), we must reduce the time for detecting the event and issuing a warning to about 5 seconds. For earthquakes within 20 km of a city, there is little one can do other than installing automatic shut-off devices for gases (for example) that can be triggered by the onset of the P-wave. Normally an earthquake that is more than 100 km away from a city does not pose a large threat to the city, because seismic waves would be attenuated by a factor of about 5 in general. There are exceptional cases due to unusual local site conditions, such as Mexico City, that will be discussed later.

4. REAL-TIME MONITORING AND EARLY WARNING

There are two different approaches in implementing an earthquake early-warning system. Nakamura (1988; 1996a; 1996b) used a single station approach, where seismic signals are processed locally and an earthquake warning is issued when ground motion exceeds the trigger threshold. Lee et al. (1996) used an array approach, where a central station processes signals from an array of stations and decides whether or not an earthquake exceeding certain threshold has occurred.

It was recognized in the 1960‘s that real-time seismic monitoring was critical to the earthquake prediction program. At that time, it usually took half an hour or more to locate an earthquake. In the late 1960‘s, J. P. Eaton, W. H. K. Lee, and S. W. Stewart demonstrated through a computer simulation that a real-time seismic monitoring system could be implemented to locate an earthquake within 1 minute (unpublished report submitted to the U. S. government). Two years later, an actual system was developed by this team at the U. S. Geological Survey (USGS) in Menlo Park (Stewart et al., 1971). Since then, numerous real-time monitoring systems have been developed and implemented worldwide.

In real-time monitoring, signals from seismic sensors in the field (either analog or digital) are telemetered to a central receiving station for processing. By real-time we mean that the results can be obtained within seconds or tens of seconds. In practice, there are several obstacles to achieving a quicker response. Large earthquakes normally occur at depth of a few tens of kilometers or deeper. It takes several seconds for seismic waves to reach the earth‘s surface where the seismic sensors are located, and several tens more seconds before sufficient numbers of sensors detect the seismic waves. In the experimental earthquake early-warning system in Hualien, Taiwan, a 10-second or less response time has been achieved for earthquakes occurring inside or near the dense array with sensor spacing of about 2 km. However, such dense deployment of sensors is not economical to cover a large area in real practice.

In essence, a real-time seismic monitoring system consists of: (1) sensors deployed in the field, (2) telemetry, (3) a central receiving station where real-time data acquisition and processing are performed, and (4) if an potential damaging earthquake has been detected, then results are communicated via one or more communication channels to users. For an earthquake early-warning system based on real-time seismic monitoring, we must achieve a response time that users can take actions before strong shaking arrives. Unfortunately, most urban areas of the world (except Mexico City and a few others) are not situated at a favorable distance from earthquake source regions for earthquake warning to be effective. Recent damaging earthquakes, such as Northridge and Kobe earthquakes, occurred in heavily populated areas, too close for any earthquake early-warning system to be useful before strong shaking arrived.

It is interesting to note that the earthquake early-warning systems in operation in Japan and Mexico were developed by engineers in response to a practical need. Whereas the real-time seismic monitoring systems developed by the seismologists are mostly for collecting data and for in-house research. This situation changed somewhat after the 1989 Loma Prieta, California earthquake. Rapid earthquake notification systems were developed in southern California ("CUBE", the Caltech/USGS Broadcast of Earthquakes , Kanamori et al., 1991) and in northern California ("REDI", the Rapid Earthquake Data Integration Project, Gee et al., 1996). These systems allow earthquake parameters to be broadcasted to users in a few minutes after the earthquake occurred. For the 1994 Northridge, California earthquake, rapid notification by CUBE was found very useful in emergency and recovery management (Eguchi et al., 1997).

Recently, Kanamori et al (1997) summarized the progress on real-time seismology and earthquake hazard mitigation as follows:

"Recent advances in seismic sensor technology, data acquisition systems, digital communications, and computer hardware and software make it possible to build reliable real-time earthquake information systems. Such systems provide a means for modern urban regions to cope effectively with the aftermath of major earthquakes and, in some cases, they may even provide warning, seconds before the arrival of seismic waves. In the long term these systems also provide basic data for mitigation strategies such as improved building codes."

Real-time seismic monitoring is also critical for volcano studies. In particular, the IASPEI real-time seismic data acquisition and processing system (Lee, 1989; 1990) was used in the successful prediction of the Mount Pinatubo eruption in 1991 (Kerr, 1991; Newhall and Punongbayan, 1996).

5. BENEFITS OF AN EARTHQUAKE WARNING SYSTEM

An earthquake early-warning system may provide the critical information needed (1) to minimize loss of property and lives, (2) to aid rescue operations, and (3) to assist recovery from earthquake damage.

The most effective use of earthquake early warning is to activate automated systems to prepare for incoming strong ground shaking. For example: slowing down rapid-transit vehicles and high-speed trains to avoid potential derailment, orderly shutdown of pipelines and gas lines to minimize fire hazards, controlled shutdown of manufacturing operations to decrease potential damage to equipment, and safe-guarding computer information by saving vital information and retracting disk heads away from the disk surface. All the above can be accomplished to a useful extent with a few seconds notification.

Although human response may take more than a few seconds, personal safety could be greatly enhanced if people were alerted: school children could seek cover under desks and workers could move away from hazardous positions. More importantly, early earthquake notification might reduce panic and confusion. The functions of a modern society, including civil and military operations, will be less likely to turn into chaos if an early earthquake notification is available and drills for appropriate actions have been performed. For example, the Mexico City Alert System (and associated programs to educate the public) demonstrated its usefulness during the September 14, 1995 earthquake (Espinosa-Aranda et al., 1995; 1996).

For an earthquake early-warning system with sufficient numbers of well- distributed accelerometers (such as the realtime system in operation in Taiwan), we can estimate quickly the maximum expected ground-motion caused by an earthquake (i.e., a shake map), so that emergency response teams may be dispatched where they are needed most. In practice, such a shake map will be revised and updated as more information is received. In addition, an inventory of man-made structures and their vulnerability must exist so that loss estimation from an earthquake can be quickly assessed to aid disaster response and recovery. The usefulness of this approach is recognized, especially after the Northridge earthquake (Goltz, 1996; Eguchi et al., 1997). Recently, the Federal Emergency Management Agency (FEMA) of the United States introduced a risk assessment methodology -- Hazards United States (Hazus) to assist emergency managers in estimating earthquake risk in their jurisdictions (Nishenko, 1998). The shake map produced by an earthquake early-warning or rapid notification system is required for Hazus' approach in estimating loss after an earthquake disaster.

As noted before, few cities are favorable located so that an earthquake warning message can be effectively used before strong shaking occurs. Although Mexico City is favorably located for earthquake early warning, the experience of the SAS in Mexico City indicates that it is not easy to manage a public earthquake early-warning system. Nevertheless, an earthquake early-warning or rapid notification system is an important tool to provide the necessary information (e.g., a shake map) for effective earthquake mitigation and to monitor the seismicity after a disastrous earthquake.

6. EARTHQUAKE EARLY-WARNING SYSTEMS IN OPERATION

We will now briefly review a few earthquake early-warning systems that are currently in operation around the world. The two operating systems in Japan were developed under the leadership of Y. Nakamura and were designed to issue earthquake warnings for the railway operations (Nakamura, 1996a; 1996b). J. M. Espinosa-Aranda and associates (Espinosa-Aranda et al., 1995; 1996) developed the Seismic Alert System operating in Mexico. Its purpose is to communicate an emergency message to the public in Mexico City. Two research-oriented systems have been implemented in Taiwan as a joint effort of the Central Weather Bureau, the Southern California Earthquake Center, and the U. S. Geological Survey (Lee, 1995; Lee et al., 1996; Shin et al., 1996; Teng et al., 1997; Wu et al., 1997). We will also mention a few earthquake notification systems that are potentially capable of earthquake early warning, but whose main purpose is to provide rapid notification for emergency and recovery management immediately after a damaging earthquake.

6.1 Earthquake Early-Warning Systems in Japan

For more than twenty years, Japan has benefited from an earthquake early-warning system on their Japan Railway trains, including the “bullet” trains (Nakamura and Tucker, 1988). This system consists of alarm seismometers installed every 20 km along the lines (see Figure 2). Currently, an intelligent earthquake warning system called UrEDAS is being implemented in Japan (Nakamura, 1988; 1996a; 1996b). UrEDAS (Urgent Earthquake Detection and Alarm System) uses a single station instead of a network approach. An UrEDAS system detects initial P-wave motion of an earthquake and estimates its location and magnitude within about 3 seconds. Using the location and magnitude data, it then issues an alarm for the area of expected damage. By March, 1992, fourteen UrEDAS had been installed along the Tokaido Shinkansen line and a total of about 30 UrEDAS are now in operation (Nakamura, 1996b).

During the January 17, 1995 Kobe earthquake, the alarm seismometers issued alarms within a few seconds one by one. All Tokaido UrEDAS (except at Gozaisho) judged the Kobe earthquake as harmless for the bullet trains and did not issue an alarm. However, the UrEDAS at Gozaisho, which is nearest to the bullet train line, did issue an alarm at about the same time as the older alarm seismometers. These results indicate that both old and new warning systems for the bullet trains functioned properly as designed.

6.2 The Seismic Alert System in Mexico

Mexico City suffers from considerable earthquake damages even though the earthquake sources are typically about 300 km away. The Michoacan earthquake of September 19, 1985 killed about 10,000 people and left tens of thousands homeless in Mexico City. After the 1985 earthquake, a seismic alert system was designed and implemented by the Centro de Instrumentacion y Registro Sismico (CIRES) under the direction of J. M. Espinosa-Aranda. This system is named the Seismic Alert System (SAS), and it consists of four units: seismic detection, telecommunications, central control, and radio warning. The seismic detector system has 12 digital strong-motion field stations along 300 km of the Mexican coast at 25 km spacing as shown in the top portion of Figure 3. Each field station monitors the seismic activity within a 100-km radius and detects and estimates magnitude of an earthquake within 10 seconds of its initiation. If the estimated magnitude is greater than 6, a warning message is sent via the telecommunications unit to the central control unit in Mexico City. A public alert signal is sent through the radio warning unit if two or more field stations confirm the occurrence of the earthquake.

The local magnitude is estimated for epicentral distances closer than 100 km, using an empirical relation embedded in each field station, this relation uses mainly the root mean square acceleration and its average evolution. The decision of emitting the early warning is taken by the central control system in Mexico City after receiving the estimates of other stations. During the operation of SAS, there have been some inaccurate magnitude estimations. To solve this, the empirical relation has been periodically adjusted using new earthquake data acquired by the system. Also, a minor adjustment to the central control unit enhanced the system by allowing general alerts only when at least two field stations estimate the magnitude of the earthquake as greater than 6.

In addition to implementing a practical earthquake early-warning system, the Mexican group also paid attention to the utilization of the seismic alerts by the public. A comprehensive education program with drills was also implemented. The success of the SAS required support of the Mexican government and the cooperation of the public. Furthermore, Mexico City is favorably located with respect to earthquake sources so that there is sufficient time to react to earthquake warnings. Because the Mexico City system is the only earthquake early-warning system in operation that is issuing an alert to the public when a large earthquake is detected, we will devoted a section on its societal experience later in this paper.

6.3 Earthquake Early-Warning Systems in Taiwan

A strong-motion instrumentation program in Taiwan (to install an equivalent of 1,000 three-component digital accelerographs) was begun in 1991 by the Central Weather Bureau (CWB). During the instrument acquisition, CWB was able to specify accelerographs capable of digital stream output so that they can be easily integrated into the existing telemetered seismic network.

In implementing the prototype earthquake early-warning systems in Taiwan (Lee, 1995; Lee et al., 1996; Teng et al., 1997; Wu et al., 1997), two approaches were explored. The first was to develop a dense telemetered accelerograph network (covering a very small area) with real-time data processing and communication, and the second was to expand the existing regional telemetered seismic network (covering the entire island) with modern accelerographs and real-time data processing and communication. In both cases, existing commercial hardware and the published IASPEI software (Lee, 1989; 1990) were used to minimize the development cost.

A prototype system was implemented in Hualien, Taiwan, to explore the use of modern technology for earthquake early-warning purposes. The prototype system consists of 12 remote three-component accelerometers telemetered digitally via 9600-baud telephone lines to the CWB Hualien Station. At the Hualien Station, the incoming digital signals are processed in real time and the results are telemetered to the CWB Headquarters in Taipei for control and display (Chung et al., 1995).

Another prototype system was implemented in Taiwan using the existing telecommunication facilities of the Taiwan Regional Telemetered Seismic Network (with 75 short-period, 3-component seismic stations) operated by CWB. This network uses only half of the bandwidth of 9600-baud telephone lines for telemetry. As first pointed out by T. L. Teng, the remaining half of the bandwidth of 9600-baud telephone lines can be utilized to telemeter data to CWB Headquarters without any increase in operational costs. With the availability of digital accelerographs capable of digital data stream output and the IASPEI real-time seismic monitoring hardware and software, CWB implemented a real-time, regional, telemetered strong-motion network for rapid response in Taiwan with very little additional capital and operational costs. A technical description of this system and its performance may be found in Shin et al. (1996), Teng et al. (1997), and Wu et al., (1997).

The main purpose for these two prototype systems in Taiwan is for research and development of methods and techniques for earthquake early warning. The results are not intended for immediate public release. The Taiwan Central Weather Bureau realized that without a strong program for educating the public on earthquake warning response, they are not yet ready to release earthquake warning messages to the public.

6.4 Other Systems

In addition to the systems described above, there are several other rapid response systems with potential earthquake early-warning capability. We will just mention a few examples. A rapid response system is operating in Australia (Gibson et al., 1996). Since 1980's, the U. S. Geological Survey (USGS) in Menlo Park has an earthquake rapid response system for in house use. In recent years, the California Institute of Technology (Caltech) and the USGS have a "CUBE" (Caltech/USGS Broadcast of Earthquakes) system in operation in southern California (Kanamori et al., 1991). The University of California at Berkeley in collaboration with the USGS has a "REDI" (Rapid Earthquake Data Integration) system in operation in northern California (Gee et al., 1996; 1997). Since 1994, CUBE and REDI have collaborated to broadcast earthquake information for all of California (Kanamori et al., 1997).

More significantly, a multi-purpose system is being developed in southern California by Caltech, USGS and the California Division of Mines and Geology (Heaton et al., 1996; Mori et al., 1998). It is called the “TriNet” project and has the following objectives:

- To provide ground shaking data within minutes of a damaging earthquake so that the effectiveness of emergency response can be enhanced.
- To record ground motion data for research and for improving building codes.
- To develop a prototype earthquake early-warning system.

7. SOCIETAL EXPERIENCE OF THE PUBLIC SEISMIC ALERT SYSTEM IN MEXICO CITY

We will now turn to the Mexico City experience with a public earthquake early-warning system in operation for some years. The effectiveness of a public earthquake early-warning system demands both the ability to provide alert and to have an adequate population response. The issuing of the seismic alert is only one element in the process. The preparedness of city residents to respond is fundamental. Drills and education are very important to achieve the proper response to the earthquake alert signal. The magnitude 8.1 Michoacan earthquake of September 19, 1985 killed about 10,000 people and injured 30,000 in Mexico City. The heavy loss of lives was due in part to the soil conditions and structural characteristics of buildings, but also to lack of preparedness for rapid response in case of big earthquakes (Esteva, 1998).

The development and implementation of the Seismic Alert System (SAS) has been sponsored by the Mexico City Government Authorities since 1989. The SAS began operation in August 1991 with only a few users. By the end of 1992, SAS was providing the early earthquake warning to some public elementary schools on an experimental basis. It was opened as a public service using the commercial radio stations in August 1993, after the successful SAS alert that gave early warning signals between 65 to 73 sec. in advance of ground shaking during two Guerrero earthquakes, (magnitude 5.8 and 6), on May 14, 1993 (Espinosa-Aranda et al., 1995). This administrative decision opened the challenge of how to prepare and educate a population of 20 million people in Mexico City.

The planning for the dissemination and education program of the early warning signal was conducted taking into account the opinions of public and private organizations of emergency response, government officials, lifeline administrators, disaster researchers and the general public. Six public deliberations were carried out in 1992, (Fundacion Javier Barros Sierra, 1992) giving conclusions that were used to set up the education programs.

7.1 Disaster Prevention and Public Response Education Programs

The program for rapid response for public and private schools for children in Mexico City started after the September 1985 earthquakes. The Secretariat of Public Education proposed the practice of preventive actions and since 1992, response plans in the schools have been drawn up as part of the earthquake hazard reduction. Evacuation drills at schools are held monthly and in some cases with greater frequency. Officially, the education program for rapid response has become a part of the Mexico City public school program.

Earthquake education and response readiness training is carried out in all public schools of Mexico City. The Secretariat of Publication Education has instructed all Mexico City schools to listen to radio broadcast and to carry out the response procedures if the SAS generates a warning signal.

To reach the average Mexico City residents, the government of Mexico City developed and disseminated a brochure that explained the SAS to 2 million households at no charge. The brochure describes how the SAS works and gives instructions about how the residents should respond to an alert, as well as advice on preparedness activities, actions to take during an earthquake and after the shaking has ceased.

Additionally a radio spot has been transmitted repeatedly during the day by the radio stations. The announcement begins with the tone of the seismic alert and then continues giving some recommendations based on the instructions brochure. Also some additional literature has been published explaining the SAS basics, what magnitudes of earthquakes can be detected and which seismic zone is instrumented.

Despite these efforts to educate the average citizen, there has been lack of continuity in the dissemination of brochures and transmission of radio spots. The delivery of brochures was carried out only once, and radio spots were issued for only 11 months, starting in June 1993. Additionally, earthquake drills for the average city resident have not been carried out frequently. Systematic actions like training, field testing responses in advance of emergencies, updating plans and evaluating activities to enable timely response have been left to a few local community emergency response organizations. However, in January 1996, an Emergencies Act was approved by the Congress of Mexico City. Chapter II of this Act promotes the organization and training of civil response groups by the neighborhood associations.

7.2 September 14, 1995 Earthquake: Mexico City SAS Public Response

At 8:04 a.m. on Thursday September 14, 1995, a magnitude 7.3 earthquake occurred in Copala, Guerrero, Mexico, approximately 150 km east of Acapulco and 300 km South of Mexico City. There was considerable damage in coastal towns near the epicenter, although there was no major damage or casualties in Mexico City. This earthquake was felt strongly in Mexico City, amplitudes of ground motion were about 20% of those from the September 19, 1985 Earthquake (Anderson, et al. 1995), with a maximum acceleration of about 73 gal recorded in Tlahuac.

This earthquake was quite significant, because SAS early warning was activated and the majority of AM-FM commercial radio stations in Mexico City broadcasted the alert signal to the public, 72 seconds prior to the arrival of the strong ground shaking as shown in Figure 3.

The earthquake occurred during the peak hour on a working day, at a time many people were already at or were going to their normal place of employment. Normally the METRO and public transportation is crowded. Standard hours for people to arrive at their jobs is at 8:00 or 9:00 a.m. All secondary schools and universities had already started classes at 7:00 a.m. Elementary schools start at 8:00 a.m.

During the September 14, 1995 Copala earthquake, there were 98 SAS user's radio receivers distributed in Mexico City. They are classified in ten categories depending on the estimated number and type of people covered. Eighty six SAS radio receivers were activated and 12 SAS radios receivers did not work because they were not installed at that time by the users: two in the radio stations, seven in government agencies and three in emergency response centers. The following report on public response was elaborated by means of a survey carried out by telephone with the users in charge of the SAS receivers to evaluate the benefits of the early warning issued. These results are summarized in Table 1.

Public Schools. Since 1992, the Public Education Department has been a participant in the SAS education program. The public education system includes nurseries, kindergartens, schools for handicapped, elementary and secondary schools, technical institutes and universities. The total number of public school installations in the Mexico City area is 5,943 with 2,033,000 students.

At the time of the Copala earthquake, only 26 public schools were equipped with SAS radio receivers. These 26 schools covered directly, represent 14,200 children in 4 kindergartens, 16 elementary schools and 6 secondary schools. However, since the maintenance personnel in almost all Mexico City schools with no SAS receivers had been instructed by the Secretariat of Public Education authorities to monitor the radio stations and to trigger the alarm manually, the estimated number of children warned in the schools of Mexico City was 1,970,000.

The children in secondary schools were already in the classroom and the ensuing evacuations, according to education officials, were orderly and well coordinated. Most of the children in elementary schools were entering or about to enter the classroom, so they remained in the pre-designated safe places.

Private Schools. Only two private schools have the SAS receivers. The response at private schools without the SAS receivers is generally unknown. However, a comparative research about the response to the seismic alert was conducted on two private schools in Mexico City (Arjonilla, 1998), one with the SAS receiver and the other without it. The children with the SAS receiver were less stressed during and after the earthquake than the children without it and could get back to classes almost immediately.

AM-FM Radio Stations. Twenty four radio receivers with special audio controls were installed in commercial AM/FM radio stations in Mexico City, before September 1995, to switch over the standard audio program from the radio stations to a 60 sec. prerecorded message for seismic alert. This message consists of a clearly identifiable special tone and the statement "alerta sismica, alerta sismica" (in English "seismic alert, seismic alert"). This statement is automatically broadcast without the intervention of human operators. The warning message does not contain any technical information, specific guidance for protective actions, description of potential dangers or severity of the earthquake. According to the Institute of the Mexican Radio, the estimated number of listeners in the morning between 6:00 to 10:00 a.m. is 10% of the population of Mexico City area, or about 2,000,000 people. It is expected that when a person hears an early warning, he or she can communicate the emergency to another person.

Although a large number of people presumably received the SAS alert, there have been no formal evaluation of its effectiveness. There are anecdotal reports of people who were listening to the radio, heard the warning, and took some action, but there are no studies or data about the people response in general.

Subway METRO. Upon receipt of a seismic alert, the Mexico City METRO commands trains to travel at reduced speed and stop at the next station, where they open the doors. However, neither the people in the trains or at the stations were informed of the seismic alert. The estimation of people traveling in the subway was about 400,000 during the peak hours.

Housing Complex El Rosario. El Rosario is a densely populated public housing project inhabited by 200,000 people. The area is characterized by low-rise, multi-unit apartment buildings constructed between 1960 and 1970 and surrounded by open areas and recreational facilities. El Rosario has a public audio warning system connected to the SAS. At this location, a system of high power loud-speakers is installed in a tower.

The audio seismic alert broadcasted to an estimated audience of 10,000 people in the El Rosario housing complex. The audio system functioned without problem at 8:04 on September 14, providing community residents time to evacuate their apartments. Residents indicated that they were frightened when the signal sounded but responded by turning off gas and lights and evacuating their buildings according to established procedures, with the assistance of residents assigned to direct people to pre-designated evacuation routes and outdoor assembly locations. There were no reports of panic behavior such as running, shoving, or other actions associated with extreme fear and flight reactions.

The next three categories appears as "Other" in Table 1.

Emergency Response Centers. The most important centers were covered, among them the Civil Protection Agency, the Mexican Red Cross, the Central Agency for Disaster Prevention, the Police Department of Mexico, and the Central Command of the Mexican Army. A total of 13 SAS radio receivers were installed. It is estimated that 2,400 people were warned in these sites during the Copala earthquake. The emergency response centers of Civil Disaster Management office, Public Works Department and emergency services alerted their personnel. The police also were alerted and started a general inspection in the city to locate damages.

Government Agencies and Public Buildings. People who received the seismic alert signal in these sites are white collar employees with some training in evacuation procedures. The estimate of people warned is 3,900 during the Copala earthquake.

Universities and CIRES Technical Personnel. Six hundred undergraduate students in the campus heard the audio warning signals sent by the SAS during the September 14 1995, Copala earthquake. CIRES personnel were warned in their homes by 6 radio receivers (which are used for continuous monitoring of the performance of the SAS system).

7.3 Mexico City SAS Technical Incidents

During the SAS public operation service after August 1993, the early warning system had three problems. The first incident was a missed alarm during the October 24, 1993 magnitude 6.7 earthquake. The second was a false alarm broadcast to the public on November 16, 1993 at 19:20 local time. The third incident was a magnitude 4.6 earthquake that struck in the Guerrero and Oaxaca coast on May 31, 1995 at 6:49:47 local time. A restricted early warning to schools was issued by SAS, but because a school-type SAS receiver had been installed by mistake in one radio station, the chief reporter announced on the air that a big earthquake was about to strike Mexico City. These incidents caused some panic and anger, but no person was hurt or injured because of the false or missed alarm.

There are several factors that determine the reliability to issue the early warning signal of SAS. The most significant are the reliability of the equipment and the reliability of the method of magnitude determination. An initial attempt to calculate the reliability of the equipment was made using the data from the operation results of the system from September 1991 to July 1993. In this analysis the statistics of failures observed in both hardware and software subsystems, the information about what components or subsystems are most failure prone, the sources of failures, schedule in maintenance, availability and mean time between failures were evaluated to determine the reliability of the equipment. This estimate was R=0.9764 (Jimenez et al., 1993), and did not include the radio receivers of users that receive the early warning signal. When extended until May 1998, the reliability analysis was R=0.9950. The reliability enhancement was due mainly to the completion of the redundant communication path between Guerrero and Mexico City. Also the reliability of the method of magnitude determination was evaluated by the Centro de Investigacion Sismica (CIS) de la Fundacion Javier Barros Sierra, with an initial result of R=0.89 detecting and estimating earthquakes of greater than 6.

The public education, training and drills have permitted an adequate response from part of the public in Mexico City. The best response was from the public schools with a population of children with ages 5 to 15, which have the highest level of training and experience. But this good response of children depends on the continuous application of education programs for earthquake hazard reduction.

Today not all the guidelines and recommendations of the public deliberations for the SAS application (Fundacion Javier Barros Sierra, 1992) have been carried out or been continuously applied. For example, the problem of educating the average Mexico City resident still remains. Although the 1996 new law for civil protection promotes more civil response groups and emergency preparedness, there is only a limited budget to promote these actions, so the problem still remains. The limited deployment of radio receivers in schools, public buildings and industry, at present has not generated controversy. As further deployment of the system proceeds, the system will be more complex and difficult to maintain with a limited budget. There will be greater social and economic consequences as critical processes and functions are unnecessarily curtailed or disrupted in a false alert or malfunction.

Contrary to speculations, when a SAS false alarm was issued on November 16 1993, to an estimated radio audience of 2,000,000 people, during rush hour in a city of 20 million people, common sense prevailed. Before that, an argument used against disseminating the seismic alert to the public was that many people could die or get badly injured because of panic. Although some people were already trained for disaster situations when the false alarm was triggered, the majority of the public was not, and nobody was killed or injured. This November 16, 1993 lesson, should be reviewed and publicly discussed, with the aim to promote drills for rapid response to the seismic alert broadcasted by the commercial radio stations. Until now no training for the general public has been performed to promote a proper response to a seismic alert issued by radio.

7.4 Remarks

Although the early warning for the Copala earthquake was successful, the problem of a warning in a scenario with an earthquake striking at night still remains. With the majority of people sleeping and the radios turned off there is no chance of taking the 60 second advantage. To solve this problem a project has been proposed to the government to implement an all hazards radio network that will operate in the public service band between 162.400 and 162.550 megahertz (MHz) which could be used to transmit earthquake early warning signals. A low cost alert radio receiver tuned to these frequencies has been developed and successfully tested. The audio of this device can be activated even if it is turned off. The cost of this radio receiver is about 40 to 80 US dollars and it could be used to receive other emergency information, besides a seismic alert. Unfortunately no dedicated frequencies have actually been allocated for emergency broadcast purposes.

The issue about the usefulness of a public earthquake early-warning system has been answered in part by the September 14, 1995 earthquake. Major earthquakes which are likely to cause damage in Mexico City are from the Guerrero coast, and there is sufficient time for an earthquake warning. The SAS is a low cost project, but has a high benefit return for residents of Mexico City. The number of people reached by the early warning in this seismic event was about of 4 million persons, with almost 2 million of children responding adequately. From 1991 to 1997 the SAS project had a cost of $1.2 million US dollars for development and installation and $400,000 per year for operation and maintenance.

Although establishing a warning effectiveness factor or measure is somewhat ambiguous, the experience of the September 14, 1995 earthquake demonstrated that the combination of adequate public education, training, drills and a properly issued warning, can reduce social damages in case of a major Guerrero earthquake. The education programs improved the capacity to respond to earthquakes. Residents of seismically vulnerable regions can be expected to respond to a brief warning in a controlled, rational and adaptive manner as was demonstrated by the performance of students in the Mexico City public schools. Timely warnings which are heeded save lives.

8. FUTURE PERSPECTIVES

For a city that is favorable located with respect to potential earthquake source regions, a practical system for earthquake early warning can be implemented at a modest cost of a few million U.S. dollars. Recent results from the Seismic Alert System in Mexico City are very encouraging. It is interesting to note that the development of earthquake early-warning systems was first carried out outside the "mainstream" of earthquake research program of Japan and Mexico. Fortunately, the need of rapid earthquake information for earthquake response and recovery is well documented (Goltz, 1996; Eguchi, et al., 1997). In addition, Kanamori et al. (1997) have presented scientific and societal reasons for developing real-time seismology for earthquake hazard mitigation, including earthquake warning capability.

So far, only the Mexican SAS issues earthquake warning directly to the public. Because of different political, legal, and economic systems in different countries, it may be difficult to apply the Mexican experience to other countries. A false warning can cause large economic loss and legal battles in countries like the United States.

There are a few hundred regional and local seismic networks in operation around the world. With recent advances in real-time seismic monitoring, upgrading these seismic networks for rapid earthquake notification is a goal that can achieved with a relatively small cost, as shown in the Taiwan case. Many seismic networks have already recognized this potential and are working hard to achieve this goal. For example, Teng et al. (1997) showed that shake map, effective epicenter and effective magnitude could be achieved within about one minute for an upgraded telemetered seismic network in Taiwan. The TriNet project (Mori et al., 1998) is making major improvements for southern California earthquake monitoring. We believe that most existing seismic networks can be upgraded to provide useful information (such as a shake map) within minutes after a strong earthquake occurred. However, to use this information effectively (especially as earthquake early-warning messages) requires collaboration of seismologists, earthquake engineers, and emergency response managers, and education of the public. Implementing an arthquake early-warning or rapid information system is very desirable for many urban areas of the world that are threaten by earthquakes, because it stimulates the public to consider the critical issues involved in earthquake hazards mitigation, including education, planning, and response.

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Table 1. Mexico, City Seismic Alert Sistem performance in the September 14, 1995, M7.3 “Copala” Gro. earthquake.

USER ORGANIZATION	RECEIVERS ACTIVATED	PEOPLE WARNED	COMMENTS
Public schools	26	1,970,000	Children reached directly by 28 radio receivers, plus those informed by listeners alert operators.
AM/FM Radio stations	22	2,000,000	People listening radio on peak hour.
Subway METRO	2	400,000	People traveling on peak hour.
Housing complex el Rosario	1	10,000	Residents of housing complex.
Other	35	9,000	Emergency response centers, Government agencies, Public buildings, Private schools, Universities and CIRES technical personnel.
TOTAL	86	4,389,000	

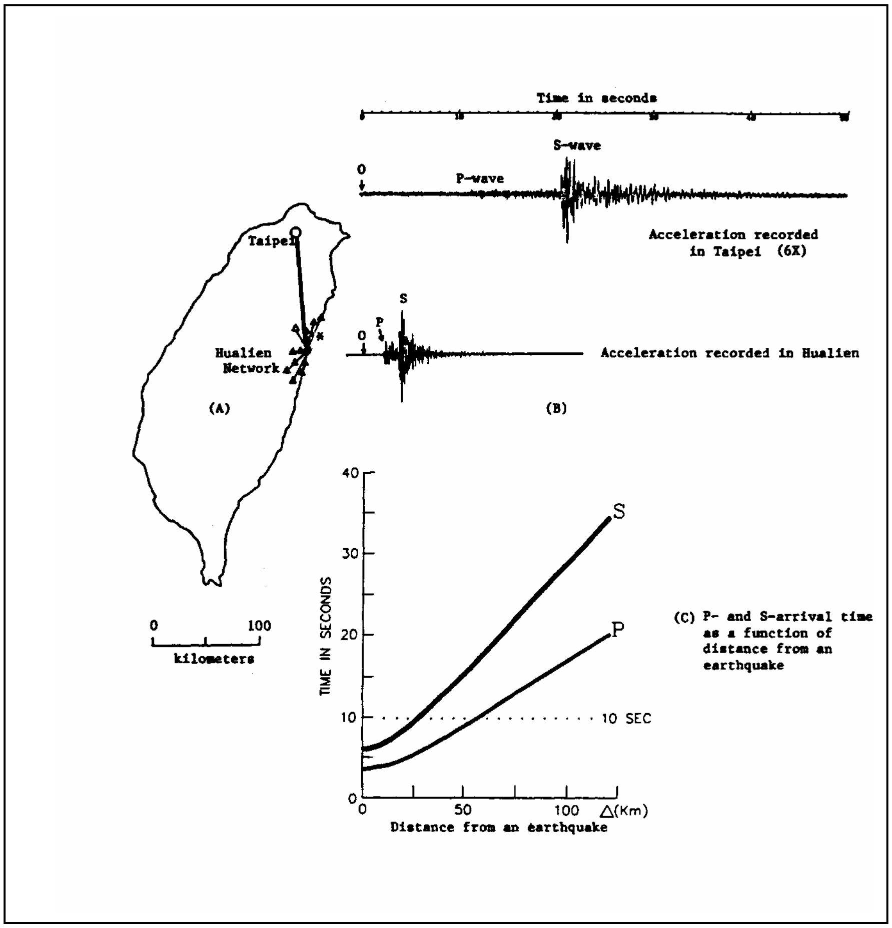

Figure 1. A prototype earthquake early warning system in Hualien, Taiwan.

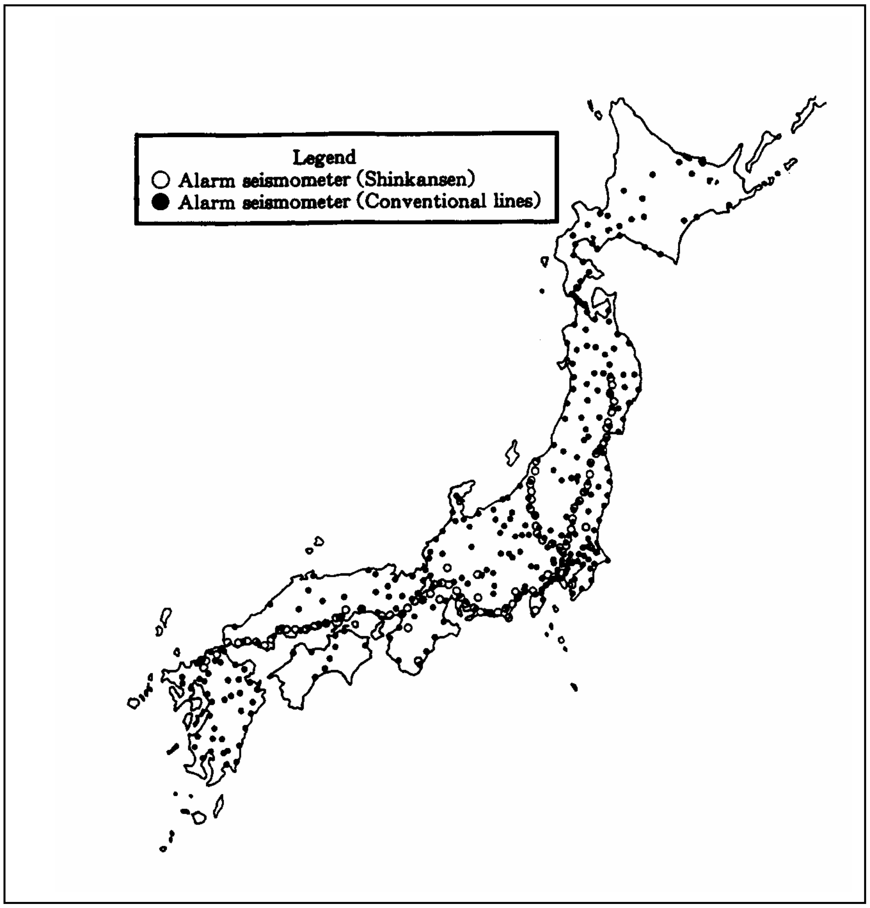

Figure 2. Distribution of Japan Railway's alarm seismometers (courtesy of Dr. Y. Nakamura).

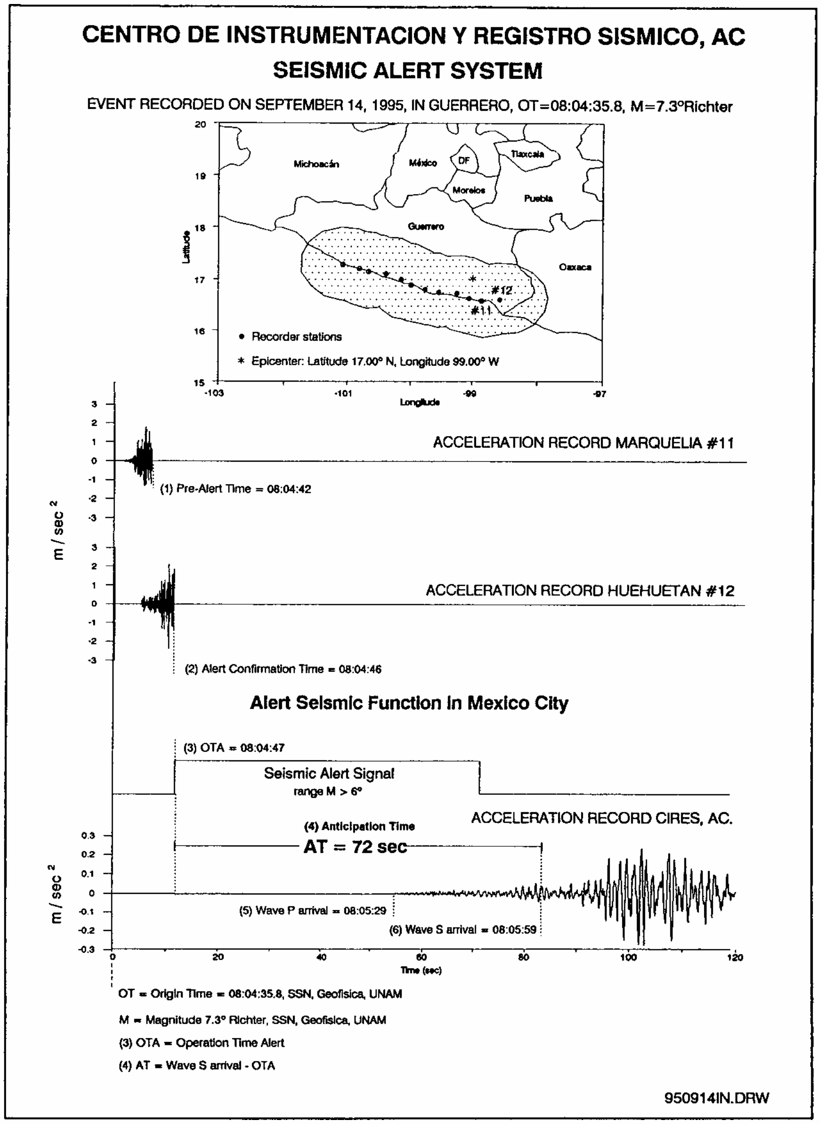

Figure 3. Time diagram of early warning advantage in Mexico City, September 14, 1985.