# Real-time seismology and earthquake hazard mitigation

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**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.**

If the impact of future earthquakes is to be effectively reduced, seismic hazards need to be addressed on several different timescales. On the timescale of decades, land use regulations and building codes need to be improved. On the timescale of a few years, measures aimed at preparing for possible earthquakes should be encouraged at personal and community levels. On shorter timescales, months to days, accurate earthquake predictions of size, location and time would be required. However, because of the extreme complexity involved in earthquake processes, reliable short-term prediction is not possible at present (see Box 1). Furthermore, even if such prediction should become possible, large earthquakes in densely populated urban areas are likely to cause extensive damage and disruption to society. To minimize the immediate impact of large earthquakes in such areas, we advocate a strategy of taking full advantage of recent advances in seismology, sensor, computer and telemetry technologies for developing rapid and reliable real-time earthquake information systems. Despite improvements in engineering designs of individual structures, modern urban and suburban areas as a whole are more vulnerable to earthquakes than ever.

The purpose of these modern earthquake information systems is to give rapid notification of the earthquake parameters (time, location and magnitude) and estimates of ground motion (acceleration, velocity, displacement, spectral amplitude and so on), in order to assess where emergency response is most needed and to estimate the overall societal impact of the event. These systems will also contribute to shortening the recovery time following major earthquakes by allowing rapid determination of what resources are needed for rebuilding and recovery after the event[1–3]. In highly industrialized areas, minimizing the response time after an earthquake is important for search and rescue efforts aiming to protect life and property. Further reducing the recovery time is critically important for utilities, communication, transportation, financial companies, commerce and local industries. The recent earthquakes in Northridge, California, and Kobe, Japan, clearly demonstrated the need for such systems, where both the response time and recovery time could have been shortened had sufficient information been available. For example, during the Kobe earthquake, because seismic networks and communication systems were disrupted by strong shaking, the full extent of the damage was not known to the central government in Tokyo until many hours later.

Today, real-time systems are capable of providing basic earthquake information within minutes, and in the future this could be reduced to tens of seconds. In some cases, facilities will receive this information even before ground shaking begins (early warning). This may allow for clean emergency shutdown or other protection of systems susceptible to damage, such as power stations, transport and computer systems. As an example of the use of early warning technology, the telecommunication networks are interested in collecting data on network performance during and immediately following a major earthquake. Such data are needed for designing future improvements of the telephone systems.

Perhaps the strongest rationale for deploying an extensive network of versatile seismic stations is that it will lead to a much better understanding of earthquake ground shaking. Ground motions from a variety of earthquake sizes and locations will allow us to distinguish the effects of wave propagation (which do not vary for earthquakes in the same location) from the effects of the earthquake rupture. This will ultimately provide much better predictions of the distribution of ground motions in future earthquakes. Furthermore, quantitative measures of building performance in earthquakes can only be achieved if shaking during damaging earthquakes is recorded with spatial density sufficient to characterize the ground motion.

**Box 1 Earthquake prediction**

In a narrow sense, an earthquake is a sudden failure process; in a broad sense, it is a long-term, complex process of stress accumulation and release occurring in a highly heterogeneous medium, the Earth. Considerable advances have been made in the past several decades in understanding crustal deformation and stress accumulation processes due to plate motion, rupture dynamics, friction, interaction between faults, fault-zone structures and nonlinear dynamics. Thus, it is possible to predict to some extent the seismic behaviour of the crust in the future from various measurements taken in the past and at present. But even a simple mechanical model of earthquakes exhibits very complex behaviour, suggesting that earthquakes are essentially a chaotic process and are predictable only in a statistical sense[22]. In many conceptual models, the magnitude of an earthquake is determined by the length of the rupture. In these models, every small earthquake that occurs has the potential to grow into a large one, but in most cases the rupture arrests in a short distance[23]. As there are 100,000 times more earthquakes of magnitude 2 (M2) than of magnitude 7, it may not be possible to predict which M2 will grow into an M7 earthquake.

Even if the physics of earthquakes were well understood, the obvious difficulty of making detailed measurements of various field variables (structure, strain and so on) in three dimensions in the Earth would still make accurate deterministic predictions unlikely. Thus, a short-term prediction, if any is made, is bound to be very uncertain. Such uncertain predictions might be useful for those places where the social and economical environments are relatively simple, and false alarms and missed events can be socially tolerated. However, in modern highly industrialized urban areas with complex lifelines, communication systems and financial networks, such uncertain predictions might not be useful; they could inadvertently damage local and global economies.

## Real-time earthquake information system

The idea of using rapid earthquake information for emergency operations is not new[4,5], and several systems have been developed in Japan, Mexico, Taiwan and the United States. The following are some examples.

*Japan*. In the late 1950s, simple seismometers were installed for a railway alarm system. Since the operation of the Bullet Train started in 1964, an automatic system to stop or slow down trains during strong earthquakes has been developed. The most recent system, UrEDAS, uses a sophisticated algorithm for seismic detection and location, and has been developed for use by the Japanese railway system[6,7]. Some utility companies have also developed real-time ground-motion detection systems for emergency services for their own facilities[8]. Recently the City of Yokohama embarked on a project to deploy a 150-station real-time strong-motion network[9].

*Mexico*. In 1985, an earthquake of magnitude $M = 8.1$ in the Michoacan seismic gap, about 320 km west of Mexico City, caused very heavy damage to the city. As a similar large earthquake is expected in the Guerrero seismic gap, about 300 km southwest of Mexico City, a seismic alert system (SAS) was developed in 1991 with funding from a private foundation[10]. This system has a specific objective: to detect $M > 6$ earthquakes in the Guerrero gap with a seismic network deployed in the gap area, and issue an early warning of strong ground motion to the residents and authorities in Mexico City. As it takes about 100 seconds for seismic waves to travel from the Guerrero area to Mexico City, this system could provide an early warning with up to 60 seconds lead time. When a $M = 7.3$ earthquake occurred on 14 September 1995 in the Guerrero gap, this system successfully broadcast an alarm on commercial radio stations in Mexico City about 72 seconds before the arrival of strong ground motion.

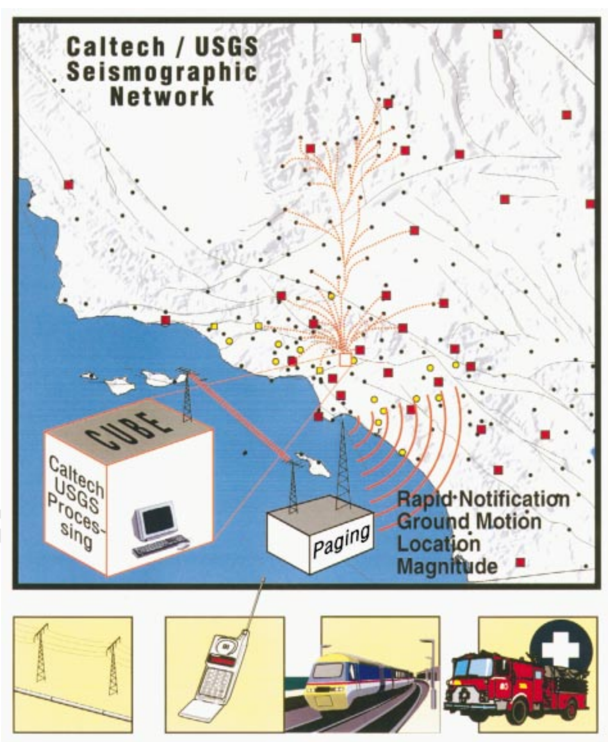


**Figure 1** Schematic diagram of the Southern California Seismographic Network (SCSN), a joint project of the US Geological Survey and the California Institute of Technology, and CUBE. The signals from the analog field seismic stations (those of the SCSN are shown as small dots, and digital stations such as TERRAscope by red squares, yellow circles and squares) are transmitted in real time to the central processing facility at Caltech in Pasadena through analog or digital telephone lines, radios, and microwave links (indicated by dashed red lines). The data are automatically processed at Pasadena, and when an earthquake is detected, its location and magnitude are determined within a few minutes. The earthquake parameters and peak ground-motion values are sent to project participants by means of a commercial paging system. The boxes at the bottom illustrate the diverse categories of the users. The pagers can also be connected to personal computers to display the location or the amplitude of ground motions on a map showing highways, railways and other infrastructure facilities.

*Taiwan*. Two prototype earthquake early warning systems have been set up in Taiwan, one for a local area near Hualien, and another for the entire island[11–13]. These systems use state-of-the-art seismic network technology, and are designed to provide critical information on earthquakes and resulting ground motions for various emergency and recovery operations.

*United States*. Rapid notification systems had been in internal use by the US Geological Survey (USGS) in California since the early 1980s. In 1990, the California Institute of Technology (Caltech) and the USGS Pasadena Office initiated the CUBE project (CUBE stands for Caltech/USGS Broadcast of Earthquakes) (Fig. 1)[14]. It was realized that closely coordinated efforts between academia, governments and private companies are essential for effective earthquake mitigation in modern metropolitan areas such as Los Angeles. One of the important objectives of the CUBE project was therefore to promote user education and close coordination efforts between various organizations with a rapid and reliable earthquake information system during major earthquake sequences. In 1993, the University of California at Berkeley and the US Geological Survey Office in Menlo Park developed a system known as REDI (the Rapid Earthquake Data Integration project) to broadcast earthquake data in northern California[15].

Real-time information can be used in many different ways. The following are some examples. (1) During the aftershock sequence of the 1989 earthquake in Loma Prieta, California ($M = 6.9$), the US Geological Survey implemented a warning system to protect construction workers cleaning up the collapsed freeways in Oakland, about 100 km from the epicentre[16]. When large aftershocks occurred, this system provided about 20 seconds of warning to the workers so they could evacuate from the potentially hazardous area. (2) During the 1991 Sierra Madre earthquake near Pasadena, workers on the Santa Fe Railway, upon receipt of CUBE information, were able to reduce the routine inspection time by 2 hours. (3) Utility companies usually do not have a large field staff for emergency operations for relatively infrequent events such as earthquakes. In an emergency, therefore, it is important for them to decide quickly on allocation of limited resources on the basis of the magnitude of the event and distribution of ground-motion intensity. (4) Some companies use earthquake information to locate the sites of possible leakage of hazardous materials and broken pipes. (5) During the 1994 Northridge, California, earthquake, a large transformer of a power company was seriously damaged by one of the larger aftershocks. CUBE helped the engineers to respond quickly enough to avoid the loss of a severely damaged transformer, thereby saving a few million dollars. (6) Immediately after a large earthquake, local telephone service, even if it is physically intact, is often disrupted because of cascading failures caused by a sudden increase in telephone traffic. If real-time data on strong ground motion is available, telephone companies may be able to avoid this problem by isolating the overloaded parts of their network. These are just a few examples, and when real-time information becomes more widely available, more applications are sure to be found.

In the following, we discuss some technical issues using the CUBE system as an example; these issues are common to many of the existing real-time systems mentioned above. CUBE uses the information provided by a 250-station seismographic network, the Southern California Seismic Network (SCSN), and more than 50 advanced digital seismographic stations, including those from TERRAscope, a state-of-the-art broad-band digital seismic network with wide dynamic range. These networks are jointly operated by Caltech and USGS. To set up the CUBE project, some hardware and software modules were added to the existing system so that earth-

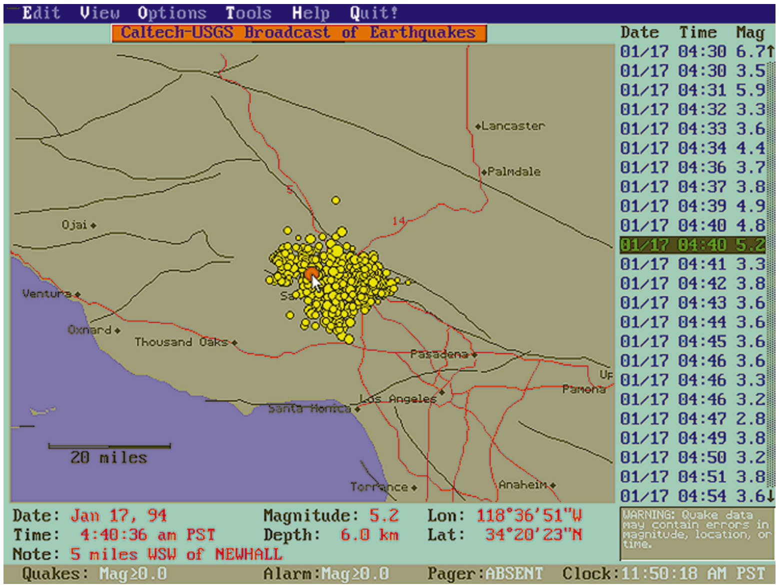


**Figure 2** The aftershock sequence of the 1994 Northridge, California, earthquake ($M = 6.7$) shown on the display that CUBE users see. The origin times of the events are listed on the right, and information on the hypocentre of the selected event (red) is displayed at the bottom. Although reporting of the Northridge mainshock was delayed (see text), the display of the aftershock activity shown here helped the emergency operators to respond quickly both to the mainshock and the large aftershocks.

quake information, such as the epicentre (location), magnitude and origin time, could be broadcast to project participants over a commercial paging system (Figs 1 and 2). Not only large earthquakes, but also all earthquakes above a preset threshold magnitude are reported, to produce a continuous display of seismicity.

In the beginning of the CUBE project, four organizations (Santa Fe Railway, Metropolitan Water District, City of Los Angeles Department of Water and Power, and Southern California Edison) participated in the project and installed the CUBE display system in their facilities' operation room. CUBE now has about 30 participating organizations and is generally considered as an integral part of the emergency preparedness plan for southern California. One of the critical elements of this project is close interaction between the CUBE operator (Caltech/USGS) and the project participants. More than 100 participants attend CUBE user meetings which are held at Caltech twice a year, and the feedback from the users plays an important role in improving the system.

The CUBE system was used effectively during the 1991 Sierra Madre earthquake ($M = 5.8$), the 1992 Joshua–Tree earthquake ($M = 6.4$), the 1992 Landers–Big Bear earthquake ($M = 7.3$) and the 1994 Northridge earthquake ($M = 6.7$). During the Northridge earthquake, failure of a key telephone line and overloading of the system caused delay in broadcasting the information on the main shock, but the spatial and temporal distributions of the ensuing aftershock activity were used by the participating agencies for guiding various emergency operations. This illustrates the importance of sending information for not only large earthquakes but also the background seismicity and aftershocks. A continuous display system is also useful for educating the users about the regional seismicity and tectonics. As large events are rare, a sudden alarm for a large event by itself would be difficult to deal with quickly unless the users were trained and could evaluate the new event location in relation to the background seismicity.

Since 1994, CUBE and REDI have joined forces to broadcast earthquake information for the entire state of California. This joint broadcast system, often called CUBE/REDI, is the only system that involves many different types of users distributed across so large an area.

## New technology and methods

In the past decade significant advances have been made in seismic sensors, digitizers, communication systems, computers and seismological methods. Introduction of these new technologies and methods can greatly enhance the capability of real-time systems such as CUBE/REDI.

As part of TERRAscope and other projects, a combination of modern broad-band seismometers, accelerographs and 24-bit digital data loggers is being used to replace the short-period sensors of the SCSN. These systems can record motion ranging from the very weak, less than $10^{-9}g$, to very strong, for instance $2g$ (where $g$ is the acceleration due to gravity at the Earth's surface). The broad-band capability is important for understanding the nature of earthquakes and resulting ground motions, which eventually will provide a better estimation of strong ground motions from future very large earthquakes (Box 2).

High-capacity digital communication systems, both land lines from the local telephone service providers (such as Pacific Bell/GTE Frame Relay) and spread spectrum radios, that are capable of sending large amounts of data rapidly and reliably are now available (Fig. 1). As the required data rate for a typical modern digital seismic station is about 20 kbps (kilobits per second), these modern

**Box 2 Why broad-band seismographs?**

Two types of seismographs are used in modern seismic networks. The first is the digital strong-motion accelerograph which records mainly strong ground motions exceeding 1% of $g$. Although the frequency band is limited, usually higher than 0.1 Hz, it provides useful data for most engineering applications. The second is the broad-band seismograph which covers a frequency band from 0.001 Hz (a period of 1,000 s) to 10 Hz, or even wider. Unfortunately, these instruments are driven off-scale when the ground motion velocity exceeds 1 cm $s^{-1}$. As the strong ground motion can exceed 1 m $s^{-1}$, these instruments are not adequate for direct strong-motion applications. Nevertheless, high-quality ground-motion data from small to moderate earthquakes recorded with broad-band instruments are important for estimating strong ground motion from very large earthquakes in the future. Because ground-motion data recorded in the proximity of large earthquakes are scarce, our knowledge about such ground motion is very limited; yet demand for such knowledge is increasing rapidly as many large structures such as high-rise buildings, bridges and large storage tanks are being built. Seismologists can now construct a model for a large earthquake as proper superposition of small to moderate earthquakes and quantitatively estimate ground motion from very large earthquakes using the data from small to moderate earthquakes. For this reason, deployment of broad-band seismographs and archiving of their data are crucial.

communication systems are more than adequate for transporting data for real-time seismic systems.

Another important consideration pertains to whether data telemetry should be continuous or event-triggered. In 'triggered' systems, only the portion of data that contains earthquake ground motion is telemetered from a field station to the central processing facility. This minimizes the telemetry cost, but the work-load on the system increases suddenly during a major earthquake, and could cause a system failure during the time when real-time data are most needed for emergency services. In contrast, in systems using continuous data transmission to the central facility, data are processed regardless of whether earthquakes are occurring. This minimizes the fluctuation of work-load, leads to more reliable event identification using the data from all the stations simultaneously, and assures more reliable operation of the system. Also, continuous data are easier to archive than triggered time series which can be fragmented and have unexpected transients at the beginning of a time window of data. Thus, if the capacity and cost of telemetry system allow continuous telemetry, it is preferable to the triggered mode.

Modern computers with multiple central processing units provide enough capability for processing data for real-time seismic systems. Telemetry between the stations and the central processing facility can be viewed as inter-computer networking which allows two-way communication to aid in diagnosis, maintenance and calibration of stations. A similar digital telemetry can be used to send information from the central facility to remote user facilities.

Data processing methods need to be expanded to accommodate users' needs. For example, for immediate emergency relief after an earthquake, it is often more important to know the spatial distribution of strong-motion parameters such as peak acceleration, peak velocity and spectral amplitudes.

Traditionally, seismic networks provide the location and the origin time of earthquakes determined from the arrival times of various seismic phases, such as P and S phases. In this case 'the location' refers to the point where the rupture initiates (the hypocentre). This practice will continue to be central to any real-time system. However, for very large earthquakes, the energy is radiated from a large area surrounding the entire fault plane, and the hypocentre indicates only where rupture starts. Thus, it is desirable to locate, in addition to the traditional hypocentre, the centre of the energy radiation, here referred to as the ground-motion centroid. In essence, the centroid must be close to the station with the largest amplitude. In practice this method has long been used by seismologists who guessed where the earthquake was from the reports of shaking intensity. With modern seismic instruments which can measure ground motion accurately, the method can be computerized to locate the strong-motion centroid[17].

## Future development

Real-time systems must be reliable and free from false alarms. As the speed and reliability of information delivery increase, these systems will be capable of issuing rapid notifications, ground motion maps and early warning to some users. Recording and archiving broad-band data from small to large earthquakes is also important for estimating ground motion from very large earthquakes, which in turn is crucial for improving engineering practice, especially for large buildings and structures. Real-time systems with modern data archiving capability can also be used to accomplish this longer-term goal. Incorporating these concepts, Caltech, USGS and the California Division of Mines and Geology recently initiated a collaborative project, TriNet, with the goal of building a state-of-the-art real-time earthquake information system in southern California[18].

Another important element is the development of tools for modelling damage to buildings and lifelines, and estimating casualties in near real-time, given the source parameters and ground-motion maps of an earthquake. Software based on GIS (the Geographical Information System) is currently being developed for this purpose. For example, the California Office of Emergency Services (OES) helped to secure 8.6 billion dollars in federal disaster relief assistance based on an estimated total loss of 15 billion dollars for the Northridge earthquake. This estimate was produced within one day of the earthquake and was based on modelled ground shaking and databases of building inventories[19]. Development of real-time damage assessment tools has continued since the Northridge earthquake, and the California OES currently operates a GIS-based system that will provide damage projections within several hours of the occurrence of an earthquake[20]. Furthermore, the GIS systems provide the necessary platform for including multi-hazard information from other types of events such as fire, flood and wind[21].

Overall, the introduction of modern broad-band seismometers, digital data loggers, communication systems and computers holds promise for building rapid and reliable systems for real-time monitoring of the distribution of strong ground motion, the essential for emergency operations and early warning systems. However, effective mitigation of earthquake hazards cannot be achieved by science and technology alone. Mitigation efforts should be closely coordinated between various emergency organizations and utility, transport and communication companies. Rapid, reliable earthquake information systems will play a key role in organizing such efforts and greatly contribute to reducing the hazard through more rapid and focused emergency response in modern urban areas. □

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