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# REAL-TIME SEISMOLOGY AND EARTHQUAKE DAMAGE MITIGATION

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**Key Words** earthquake early warning, earthquake rupture, earthquake prediction, hazard mitigation, structural control

■ **Abstract** Real-time seismology refers to a practice in which seismic data are collected and analyzed quickly after a significant seismic event, so that the results can be effectively used for postearthquake emergency response and early warning. As the technology of seismic instrumentation, telemetry, computers, and data storage facility advances, the real-time seismology for rapid postearthquake notification is essentially established. Research for early warning is still underway. Two approaches are possible: (*a*) regional warning and (*b*) on-site (or site-specific) warning. In (*a*), the traditional seismological method is used to locate an earthquake, determine the magnitude, and estimate the ground motion at other sites. In (*b*), the beginning of the ground motion (mainly *P* wave) observed at a site is used to predict the ensuing ground motion at the same site. An effective approach to on-site warning is discussed in light of earthquake rupture physics.

## INTRODUCTION

Seismology provides us with key information on the structure of Earth as well as the physics of earthquakes and other geophysical processes. At the same time, it has an important role in reducing the impact of earthquakes on our society. Accurate predictions of earthquakes would be obviously effective for reducing the damage caused by earthquakes. Unfortunately, the nucleation and rupture processes of earthquakes are governed by many factors that interact with each other in a complex fashion. Because of this complex interaction, it is difficult to make accurate predictions of earthquakes. Another practical way to use seismology for effective damage mitigation is real-time seismology. Real-time seismology normally refers to a practice in which seismic data are collected and analyzed quickly after a significant seismic event so that the results can be effectively used for postearthquake emergency response and, under favorable circumstances, early warning. Also, gaining scientific information quickly has its own merit for better understanding the process through strategically deployed instrumentation and planned field works.

The timescale involved in real-time seismology is, in most cases, minutes to hours. In these cases, by the time information is released the earthquake is over, and the information is used mainly for postearthquake emergency response, planning field works, deploying instruments, and public information services. If the information can be gained in a matter of seconds to minutes, it can be used for early warning purposes in which information on the severity of seismic shaking reaches the users before shaking begins at the user site. The technology for this is far more difficult than that for the postearthquake information system, and active research is now underway.

Recent reviews on real-time seismology and earthquake early warning systems (EWSs) are found in Kanamori et al. (1997) and Lee & Espinoza-Aranda (2002), respectively. Also, a book (in Japanese) by Kikuchi (2003) covers a broad aspect of real-time seismology. Here, we first briefly review the history and the present status, and then focus on the scientific basis of earthquake early warning.

## HISTORY

### Rapid Notification of Earthquake Information

In the late 1960s to 1970s, the U.S. Geological Survey (USGS) in Menlo Park developed a telemetered earthquake monitoring system in central California that enabled rapid location and magnitude determination of regional earthquakes (Stewart et al. 1971, Lee & Stewart 1981). At about the same time, USGS and the California Institute of Technology (Caltech) jointly operated a telemetered seismic network in southern California. Also, numerous real-time monitoring systems were developed and implemented worldwide. The basic technology for telemetering and rapid (i.e., near real-time) processing of seismic data had been fully developed by the end of the 1980s.

Taking advantage of these developments, rapid earthquake notification systems were developed with special emphasis on involving the users of such information. The Caltech/USGS Broadcast of Earthquakes (CUBE) (Kanamori et al. 1991) developed in southern California and the Rapid Earthquake Data Integration Project (REDI) (Gee et al. 1996, 2003) developed in northern California are among the early examples. These systems allow earthquake parameters to be broadcast to users a few minutes after an earthquake occurs. After the deployment of a dense broadband seismic network in southern California, called TriNet (Mori et al. 1998, Hauksson et al. 2001), a more general notification system, ShakeMap (Wald et al. 1999a,b), was developed in which the observed ground-motion data are rapidly processed to produce a map showing the distribution of strong ground motions. ShakeMaps are generated automatically, following moderate and large earthquakes, within several minutes of the earthquake origin time (Goltz 2003).

In Japan, the Japan Meteorological Agency has long been engaged in routine seismological observations, and the rapid earthquake information has been released to the public mainly through radio and television networks. Tokyo Gas Co. developed an extensive real-time system called SIGNAL (Seismic Information Gathering Network Alert System), which was put into operation in 1994 and was eventually upgraded to an even higher density network. Also, after the 1995 Kobe earthquake, the city of Yokohama deployed a high-density strong-motion network for the purpose of understanding the site responses and rapid reporting of ground motion in the event of a large earthquake. These projects are described in detail in Kikuchi (2003). At the National Research Institute for Earth Sciences and Disaster Prevention (NIED), a system called Real-Time Operation System for Earthquakes (ROSE) was recently developed (Ishida & Ooi 2002), which transmits earthquake parameters determined from the NIED's extensive seismic networks (e.g., Hi-net, F-net, KiK-net, and K-net) to various users.

In Taiwan, an ambitious program for deploying a thousand strong-motion instruments was proposed by Yi-Ben Tsai, Ta-liang Teng, and others in 1989, and it was subsequently funded by the Taiwan government in 1991–1996. Real-time applications of this dense strong-motion network were formulated by Lee et al. (1996) and Shin et al. (1996). By 1999, more than 600 free-field strong-motion stations and over 50 strong-motion arrays (each with typically 30 accelerometers) in selected buildings and bridges were deployed by the Central Weather Bureau (CWB) (Shin et al. 2000, 2003). For the 1999 Chi-Chi, Taiwan, earthquake ($M_w = 7.6$), this network produced not only reliable rapid information (Wu et al. 2000) but also a spectacular data set that was distributed rapidly to seismologists around the world (Lee et al. 2001a,b). This data set has been used for extensive research and has contributed significantly to recent developments in seismology.

## Earthquake Early Warning System

The concept of earthquake early warning dates back at least to J.D. Cooper, who proposed in November 1868, immediately after an $M = 7$ earthquake on the Hayward fault, California, the idea of an earthquake early warning system for San Francisco, California (Nakamura & Tucker 1988). Cooper proposed to set up seismic detectors near Hollister. When an earthquake triggered the detectors, 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. Unfortunately, Cooper's scheme was never implemented. Heaton (1985) proposed a modern conceptual model for a computerized seismic alert network for southern California.

The best known example of an EWS put into practical operation is the one developed by the Japanese Railway in the 1960s to slow down or stop trains before seismic shaking affected trains running at high speed (Nakamura 1988, 1989; Nakamura & Tucker 1988). Nakamura used a single-station approach, where seismic signals are processed locally and an earthquake warning is issued when ground motion exceeds the trigger threshold. This system, called UrEDAS, has been widely used in the Japanese railway system.

During the aftershock sequence of the 1989 Loma Prieta, California, earthquake ($M_w = 6.9$), Bakun et al. (1994) implemented an EWS to protect construction workers cleaning up the collapsed freeways in Oakland, approximately 100 km from the epicenter. When large aftershocks occurred, this system provided about 20 s of warning to the workers so they could evacuate from the potentially hazardous area. This is a good example in which a simple modification of an existing system can be used for practical early warning.

In Mexico, a Seismic Alert System (SAS) was developed in 1991 with the specific objective of issuing early warnings to the residents and authorities in Mexico City for large earthquakes in the Guerrero seismic gap, approximately 300 km southwest of Mexico City (Espinosa-Aranda et al. 1995). Espinosa-Aranda & Rodriguez (2003) describes the details of this system and its performance.

In Taiwan, earthquake early warning and rapid reporting were two key elements in their 1991–1996 strong-motion instrumentation program. A prototype EWS was implemented in Hualien to explore the use of modern technology for early warning purposes (Chung et al. 1995, Lee et al. 1996), whereas rapid reporting was put into routine network operation (Shin et al. 1996; Teng et al. 1997; Wu et al. 1997, 1998, 1999, 2001). The Taiwan EWS established by the CWB uses a real-time strong-motion accelerograph network consisting of 86 stations distributed around Taiwan. As shown in Figure 1, with the application of the concept of a virtual subnetwork (VSN) to the CWB seismic network (Wu & Teng 2002), the Taiwan EWS offers earthquake early warnings for metropolitan areas located more than 70 km from the epicenter. For an event with the same location as the September 20, 1999, Chi-Chi earthquake, the Taipei metropolitan area at 145 km from the epicenter would have more than 20 s of early warning time.

Recently, Allen & Kanamori (2003) demonstrated the feasibility of a short-term hazard warning using the extensive data set from TriNet in southern California. The proposed system, Elarms, could issue a warning a few to tens of seconds ahead of damaging ground motion.

In another recent development, the Japan Meteorological Agency implemented a prototype emergency earthquake alarm system, and on February 25, 2004, they started experimental use of the early warning information with universities and private organizations. The basic method is described in Odaka et al. (2003).

Other developments are included in recent national and international reports to the International Association of Seismology and Physics of the Earth's Interior (IASPEI), edited by Kisslinger (2003).

## PRESENT STATUS

As the technology of seismic instrumentation, telemetry, computers, and data storage facility has advanced, many modern high-density seismic networks have been constructed in many countries. Most of these networks have some rapid notification systems. It is fair to say that the real-time seismology in the sense of rapid postearthquake notification has been essentially established and put into practice.

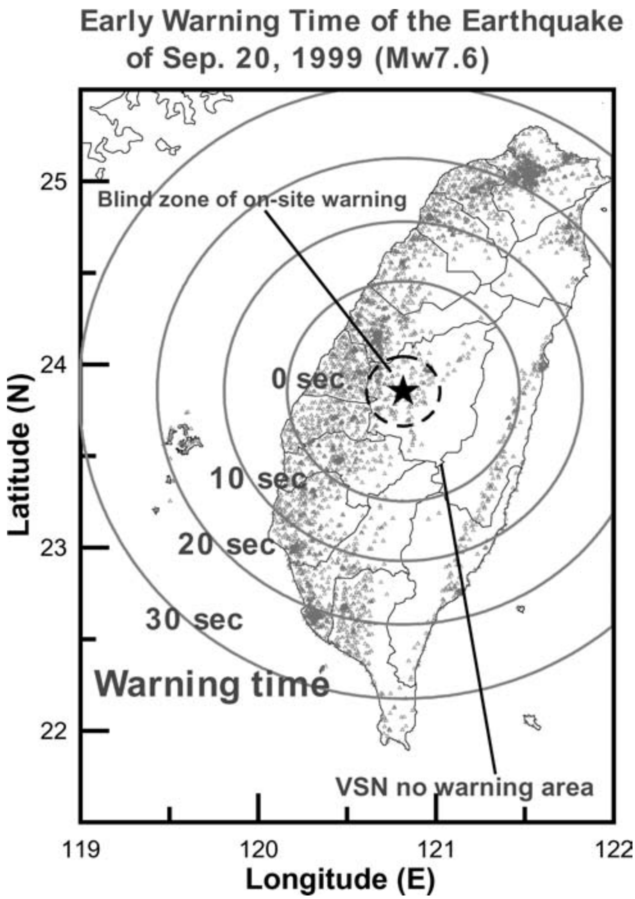


**Figure 1** Expected VSN-based EWS early warning times (indicated by *solid circles*) in Taiwan with respect to the occurrence of an event similar to the Chi-Chi earthquake of September 20, 1999. Triangles give the location of elementary schools, which can be regarded as the population density of Taiwan. The small circle (*dashed*) with a radius of 21 km indicates the boundary of the blind zone of the on-site warning method.

What remains to be done are broadening the spatial coverage, increasing the station density, and developing robust telemetry, processing, and communication systems. It is expected that, with further advances in technology, the network performance can only improve, and these networks will make solid contributions to earthquake damage mitigation, especially in modern large urban areas.

As the system improves, the information reaches the users more rapidly. Under certain circumstances, it reaches the user before ground shaking starts at the user's site, and the information becomes an early warning. In principle, no difference exists between postearthquake notification and earthquake early warning; however, for specific early warning purposes, it is more practical to distinguish early warning from postearthquake notification.

Two approaches to earthquake early warning are possible: (*a*) regional warning and (*b*) on-site (or site-specific) warning. In (*a*), the traditional seismological method is used to locate an earthquake, determine the magnitude, and estimate the ground motion at other sites. In (*b*), the beginning of the ground motion (mainly *P* wave) observed at a site is used to predict the ensuing ground motion (mainly by *S* and surface waves) at the same site; no attempt is necessarily made to locate the event and estimate the magnitude. The first approach is more reliable, but it takes a longer time and cannot be used for the sites at short distances. In contrast, the second approach is less reliable, but it is very fast and could provide useful early warning to sites even at very short distances where an early warning is most needed. The first approach has already been used in Japan, Mexico, and Taiwan (Figure 1).

In the second approach, it is necessary to make rapid estimation of the nature of the progressing earthquake or the ground motions at an early stage of its rupture process.

Beginning with Nakamura's (1988) study, many methods have been developed to estimate the size of an earthquake from the beginning. Because such estimation requires some understanding of earthquake physics and rupture processes, we focus on this point in the following section.



# SCIENTIFIC BASIS OF EARTHQUAKE EARLY WARNING

## Beginning of an Earthquake

A basic scientific question relevant to earthquake early warning is whether we can estimate the eventual size or the characteristics of an earthquake from the very beginning of the rupture process. Interesting suggestions have been made by several investigators such as Iio (1992, 1995), Umeda (1990, 1992), Ellsworth & Beroza (1995), and Beroza & Ellsworth (1996). These studies suggest that large and small earthquakes may be distinguished from the very beginning of the rupture process. The initial low-amplitude phase, called the nucleation phase, tends to last longer for larger earthquakes. In contrast, Nakatani et al. (2000) suggests that microearthquakes that start with a stronger initial rupture tend to grow larger. This trend is somewhat opposite to that suggested in the nucleation phase models. Regardless of the observed trend, implicit in these models is some nucleation process with a characteristic length and timescale that controls both the initial rupture pattern and the final size of an earthquake, at least in a statistical sense. However, other studies, such as those by Mori & Kanamori (1996) and Kilb & Gomberg (1999), found no obvious difference in the initial rupture process of small and large earthquakes. Sato & Kanamori (1999) investigated the beginning of an earthquake using the Griffith's fracture criterion and showed that the variation of fracture toughness near the fault tip can produce significant variations of the initial waveform of seismic rupture. Although this problem remains an interesting scientific question, the large variability in the beginning of earthquakes makes it difficult to use the very beginning of the rupture process for estimating the eventual size of an earthquake.

Another approach is to use the *P* wave to estimate the overall size of an earthquake. This approach may appear similar to the nucleation phase concept described above, but it is conceptually very different. Seismic fault motion generates both *P* and *S* waves, but *P*-wave amplitude is, on average, much smaller than *S*-wave amplitude. For a point double-couple source, the ratio of the maximum *P*-wave amplitude to that of the *S* wave is approximately 0.2. Thus, the *P* wave seldom causes damage, and the *S* wave is primarily responsible for earthquake shaking damage. However, the wave form of *P* wave reflects how the slip on the fault plane is occurring. In other words, the *P* wave carries information and the *S* wave carries energy. Thus, if we observe the beginning of the *P* wave over time, $\tau_0$, after the onset, we can have the information on the source at least during this time period. It is obvious that a longer $\tau_0$ would provide more accurate information of the source. However, if $\tau_0$ is too long, the early warning merit of the method is compromised. The question is how quickly, i.e., with how small a value of $\tau_0$, can we obtain the source information useful for early warning purposes.

In fact, this concept has long been used by Nakamura (1988) in the UrEDAS system for the Japanese railways. Because this point has a fundamental importance for understanding how the early warning concept works and also for eventually understanding the nucleation process of earthquakes, we discuss it in detail from a seismological point of view.

## Test with a Kinematic Model

To understand the basic principle, we consider the kinematic source model of Sato & Hirasawa (1973). This model employs a circular crack expanding from the center at a constant rupture speed *V*. The displacement profile on the crack surface when the radius reaches $\xi$ is given by the static displacement for a crack with radius $\xi$. This model has been extensively used in seismology as a useful kinematic source model for earthquakes with the magnitude smaller than 6.5. For events larger than 6.5, the circular geometry becomes inadequate.

Figure 2 shows the moment-rate function computed for a range of magnitudes, $M_w$ (moment magnitude), from 5 to 7. The shape of the moment-rate function is the same as that of the far-field displacement waveform. The important feature of this figure is that as $M_w$ increases, the width of the moment-rate function increases. If we use $\tau_0 = 3$ s, the effective period of the waveform increases with $M_w$ up to $M_w = 6.5$. If we can define a measure of the effective period of the displacement record during the first 3 s, we can use it as an indicator of the size of the event.

As a measure of the period we use a parameter, $\tau_c$, that is similar to the one used by Nakamura (1988). This parameter is determined as follows: First we compute *r* by

$$r = \frac{\int_0^{\tau_0} \dot{u}^2(t)\,dt}{\int_0^{\tau_0} u^2(t)\,dt}, \tag{1}$$

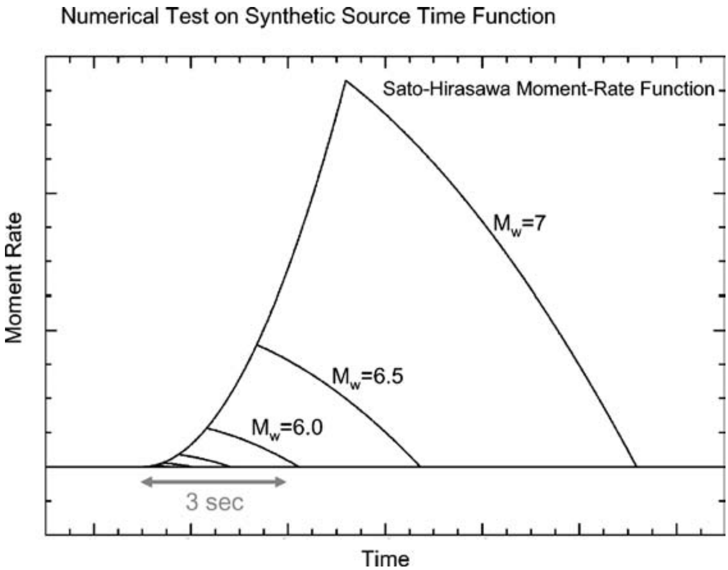


**Figure 2** Displacement waveforms computed for the kinematic source model of Sato & Hirasawa (1973). The parameters used for computation of waveforms are *P*-wave speed $=$ 6 km/s, *S*-wave speed $=$ 3.5 km/s, density $=$ 2.7 g/cm$^3$, rupture speed $=$ 2.5 km/s, applied shear stress $=$ 30 bars, polar angle of the station location $= 90^\circ$.



where $u(t)$ is the ground-motion displacement and the integration is taken over the time interval $(0, \tau_0)$ after the onset of the *P* wave. Usually, $\tau_0$ is set at 3 s. Using Parseval's theorem,

$$r = \frac{4\pi^2 \int_0^\infty f^2 \, |\hat{u}(f)|^2 df}{\int_0^\infty |\hat{u}(f)|^2 df} = 4\pi^2 \langle f^2 \rangle, \tag{2}$$

where $f$ is the frequency, $\hat{u}(f)$ is the frequency spectrum of $u(t)$ and $\langle f^2 \rangle$ is the average of $f^2$ weighted by $|\hat{u}(f)|^2$. Then,

$$\tau_c = \frac{1}{\sqrt{\langle f^2 \rangle}} = \frac{2\pi}{\sqrt{r}} \tag{3}$$

can be used as a parameter that represents the "period" of the initial portion of the *P* wave. If the waveform is approximately monochromatic with period $T_0$ and $\tau_0 > T_0$, $\tau_c$ is essentially the period of the monochromatic wave. However, if the waveform is complex, the period cannot be defined in a straightforward manner, but $\tau_c$ can still represent the effective period defined by Equation 2. $\tau_c$ is large for events enriched with low-frequency energy in the beginning. This method is different from Nakamura's (1988) in that we compute $\tau_c$ using the displacement $u(t)$ over a fixed time window after the *P*-wave onset. Nakamura used the ground-motion velocity instead of displacement and computed the integrals in Equation 1 recursively, instead of over a fixed interval.

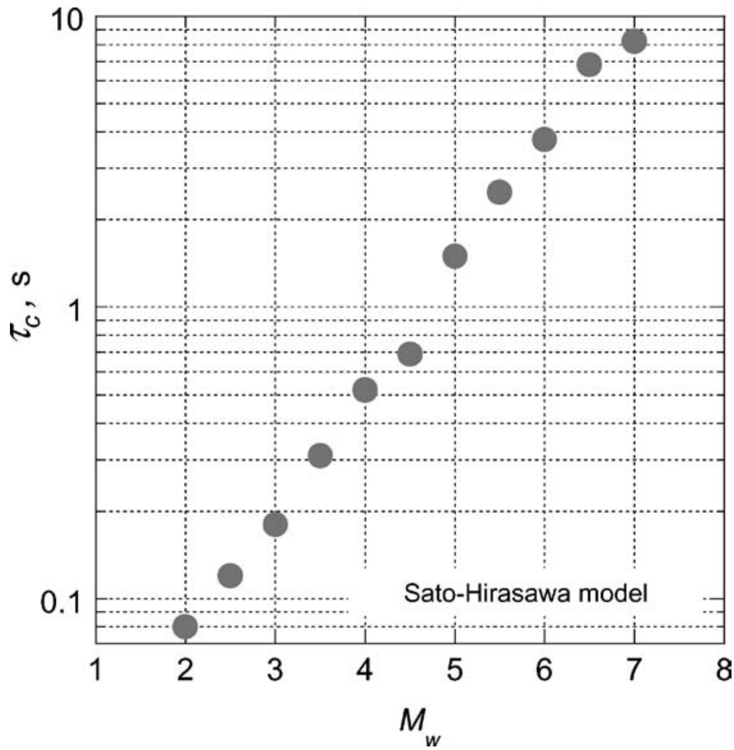


**Figure 3** $\tau_c$ in seconds computed for the displacement waveforms of the Sato & Hirasawa (1973) model shown in Figure 2. Note the saturation of $\tau_c$ at $M_w > 6.5$.

Figure 3 shows $\tau_c$ computed for the moment-rate functions shown in Figure 2 using Equations 1 and 3. As Figure 2 shows, the waveforms for the first 3 s after the onset are identical for events with $M_w > 6.5$ and $\tau_c$ saturates for $M_w > 6.5$.

The result for this kinematic source illustrates that we can estimate the magnitude using the information from the first 3 s of $P$ wave, at least for events with $M_w \leq 6.5$. If we use a longer $\tau_0$, we can estimate $M_w$ for even larger events, but the procedure takes longer time and is not practical for early warning purposes.

## Large Earthquake Data

Although the numerical experiment on synthetic waveforms demonstrates that the parameter $\tau_c$ is a useful measure of the size of an earthquake, the rupture patterns of large earthquakes are far more complex than the circular crack model used above, and it is not obvious whether this method works for real earthquakes. Figure 4*a* (see color insert) shows the moment-rate functions of recent large earthquakes. The moment-rate functions are very complex, reflecting the complex and chaotic nature of earthquake rupture process. The duration of moment-rate function is longer than 100 s for large events. At first glance it appears very difficult to estimate the overall size of an earthquake from the very beginning, e.g., the first 3 s from the onset. However, Figure 4*b*, which shows the first 15 s of the moment-rate functions, suggests that we may get some information on the total size of an earthquake even from the first 3 s. For example, the moment-rate function for the 1994 Northridge, California, earthquake ($M_w = 6.7$) is similar to the synthetic moment-rate function for an earthquake with comparable magnitude, as shown in Figure 2. As we demonstrated with the kinematic source model, it is possible to tell whether the event has reached the size comparable to that of the Northridge earthquake, i.e., approximately $M_w = 6.5$. As Figure 4*b* shows, the moment-rate functions for events larger than the Northridge earthquake are still growing at 3 s, and would yield a larger $\tau_c$ than that for the Northridge earthquake. Then, it is possible to tell from $\tau_c$ that the event is probably growing larger than $M_w = 6.5$. Beyond this point, it is not obvious how large the event is going to grow. Nevertheless, despite the complexity of the moment-rate functions shown in Figure 4*a*, it appears possible to estimate the lower bound of an earthquake from the first 3 s.

To test the method, we collected close-in records from earthquakes with magnitudes from $M = 2.5$ to 8.0 (listed in Table 1). All the displacement records are filtered with a high-pass Butterworth filter with a cut-off frequency of 0.075 Hz. Some examples are shown in Figure 5. The first 3 s from the onset of the *P* wave is indicated by two vertical dash-dot lines. Even if the wave forms are more complicated than the synthetic wave forms shown in Figure 2, the wave forms of large events are distinct from those of small earthquakes, suggesting that even from the first 3 s we can make some estimation of the magnitude of the event.

We computed $\tau_c$ with the method described above using the available close-in records for the events listed in Table 1. As shown in Figure 6, the results are consistent with the simulation results. Somewhat surprisingly, $\tau_c$ keeps increasing even for earthquakes with $M_w > 7$, without any obvious sign of saturation. Because the data set is sparse for very large events (only 5 earthquakes with $M_w \geq 7$), this result is not conclusive. Either the trend for $M_w \geq 7$ is fortuitous, or the waveforms of larger earthquakes contain more long-period energy than the simple kinematic model suggests. More close-in data are obviously needed to resolve this problem, but the consistency of the trend shown in Figure 6 with that shown in Figure 3 suggests that $\tau_c$ measured from only the first 3 s of *P* wave can be used to estimate at least the lower bound of the magnitude. In short, if $\tau_c < 1$ s, the event has already ended or is not likely to grow beyond $M_w > 6$. In contrast, if $\tau_c > 1$ s, it is likely to grow beyond $M_w = 6$. If $\tau_c > 3$ s, the event is probably larger than $M_w = 7$, but how large it will eventually become cannot be determined.

## PRACTICAL PROCEDURE FOR ON-SITE EARLY WARNING

For on-site early warning, some ground-motion parameters need to be measured rapidly during a short time after the onset of an event to issue an appropriate warning, if deemed necessary. There are many potential parameters to be used, but

**TABLE 1** Determination of $\tau_c$ from close-in records

| Event, date | $M$ | $\tau_c$, s | $N$ | $\Delta_{max}$, km |
|---|---|---|---|---|
| Taokachi-Oki, 9/26/2003 | 8.0 | 4.96 ± 1.48 | 7 | 85 |
| Chi-Chi, 9/21/1999 | 7.6 | 3.74 ± 1.31 | 8 | 19 |
| Landers, 6/28/1992 | 7.3 | 1.83 ± 0.49 | 4 | 160 |
| Hector-Mine, 10/16/1999 | 7.1 | 1.41 ± 0.59 | 5 | 89 |
| Miyagi-Oki, 5/26/2003 | 7.0 | 2.15 ± 0.77 | 8 | 29 |
| Tottori, 10/6/2000 | 6.7 | 1.45 ± 0.44 | 8 | 53 |
| Northridge, 1/17/1994 | 6.7 | 1.56 | 2 | 35 |
| San Simeon, 12/22/2003 | 6.5 | 1.30 ± 0.76 | 4 | 122 |
| North Miyagi, 7/26/2003 | 6.0 | 1.51 ± 0.94 | 8 | 27 |
| Sierra Madre, 6/28/1991 | 5.8 | 1.7 | 1 | 22 |
| Anza, 10/31/2001 | 5.1 | 0.57 ± 0.21 | 8 | 48 |
| Big Bear, 2/22/2003 | 5.1 | 0.59 ± 0.37 | 4 | 37 |
| Big Bear, 2/10/2001 | 5.1 | 0.58 ± 0.21 | 6 | 47 |
| Pasadena, 12/3/1988 | 4.8 | 0.33 | 1 | 10 |
| Coso, 7/17/2001 | 4.8 | 1.12 ± 0.38 | 7 | 95 |
| Northridge, 1/14/2001 | 4.3 | 0.34 ± 0.05 | 4 | 16 |
| N. Hollywood, 9/9/2001 | 4.3 | 0.58 ± 0.18 | 8 | 24 |
| Lucern, 7/15/2003 | 4.2 | 0.26 ± 0.07 | 8 | 70 |
| Northridge, 1/14/2001 | 4.0 | 0.29 ± 0.11 | 4 | 15 |
| Compton, 10/28/2001 | 4.0 | 0.40 ± 0.10 | 8 | 18 |
| San Marino, 9/27/2001 | 2.8 | 0.24 ± 0.10 | 7 | 23 |
| Running Springs, 5/9/2003 | 2.6 | 0.12 ± 0.02 | 3 | 31 |
| San Marino, 5/22/2003 | 2.5 | 0.22 ± 0.07 | 8 | 23 |

N is the number of records used for the measurements of $\tau_c$.
$\Delta_{max}$ is the distance to the farthest station.

for early warning purposes the ground-motion amplitude is the most obvious and important parameter.

In general, if *P*-wave amplitude is small, the event is either small or large, but at large distances, and no warning is warranted. In contrast, if *P*-wave amplitude is large at a site, the maximum ground-motion amplitude is likely to be large at the same location. However, a large *P* wave does not necessarily warrant a warning, because the event can be a nearby small earthquake with short duration. This situation is illustrated in Figure 7*a* (see color insert), which shows the relationship between the peak ground-motion acceleration (PGA, the largest of the peak ground-motion accelerations measured from the vertical and the two horizontal components) and the maximum ground-motion acceleration during the first 3 s of

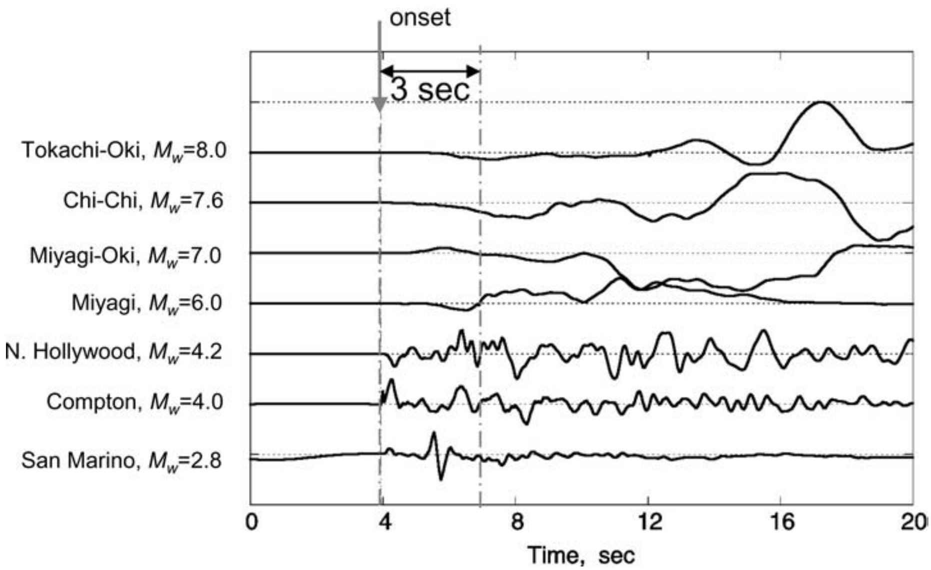


**Figure 5** The wave forms of the beginning of close-in displacement records of earthquakes with magnitudes from 2.8 to 8. The amplitudes are in arbitrary scale. The first 3 s is indicated by two dash-dot lines.

the $P$ wave (PK3s) observed at the same station. Figure 7*b* shows a similar relationship between the peak ground-motion velocity (PGV, the largest of the peak ground-motion velocities measured from the vertical and the two horizontal components) and PK3s. The 1999 Chi-Chi earthquake ($M_w = 7.6$); the 1995 Kobe, Japan, earthquake ($M_w = 6.9$); the 2000 Tottori, Japan, earthquake ($M_w = 6.6$); and the 2003 Tokachi-Oki earthquake ($M_w = 8.0$) are all damaging earthquakes, and PK3s, PGA, and PGV are all very large. However, for a nondamaging small earthquake, such as the Hollywood, California, earthquake (9/9/2001, $M_L = 4.3$), the PGA and PGV are small despite the large PK3s.

If a large $P$-wave amplitude is observed, it is important to determine immediately whether the event is small or large. For this purpose, the parameter $\tau_c$ described above can be used. If the amplitude and $\tau_c$ are measured simultaneously at a site and, for example, $\tau_c > 1$ s, the event is probably larger than $M_w = 6$ and potentially damaging, and an early warning is warranted. In contrast, if $\tau_c < 1$ s, the event is probably a nearby small event and no warning is warranted despite the large PK3s. Thus, a combination of $\tau_c$ and PK3s (or other similar amplitude parameters), both of which can be determined from the first 3 s of $P$ wave, provides a useful on-site early warning, as schematically shown in Figure 8. A use of multiple sites would be desirable to increase the reliability. This approach can provide a very rapid warning that strong ground motions are imminent at the site.

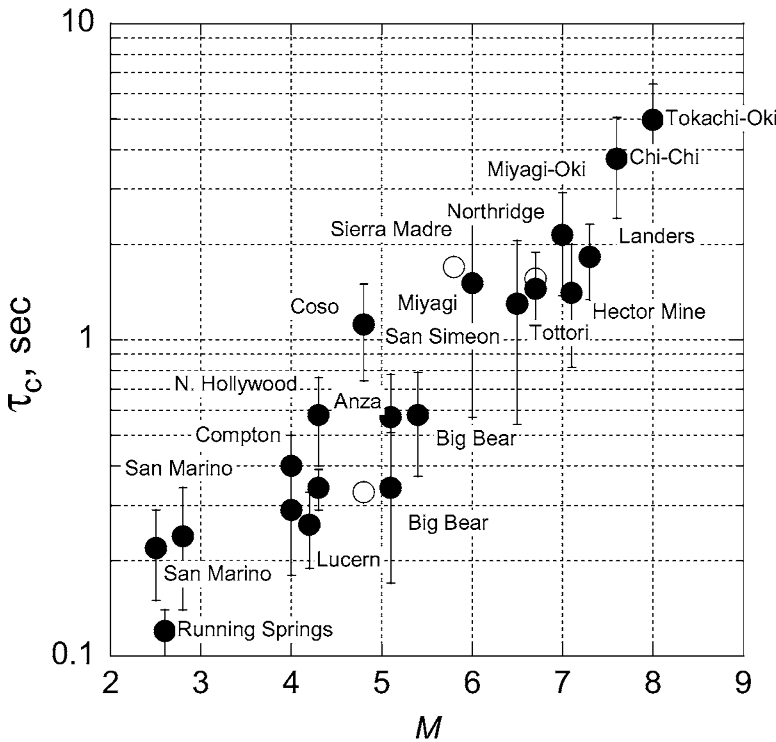


**Figure 6** $\tau_c$ computed for earthquakes with $2.5 < M < 8.0$ in California, Japan, and Taiwan using close-in seismograms. $M$ represents $M_w$ and $M_L$(local magnitude) for $M \geq 6$ and $M < 6$, respectively. Details are given in Table 1.

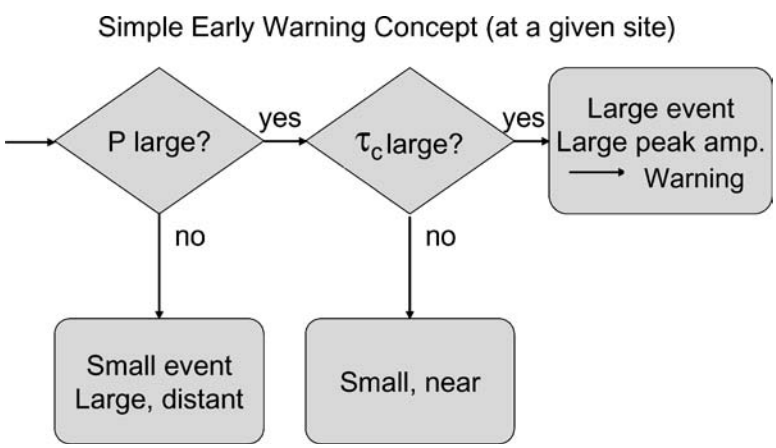


**Figure 8** A simple scheme for on-site early warning.

The method illustrated above is similar to that developed by Nakamura (1988) and Allen & Kanamori (2003) in which the period parameter $\tau_c$ is used. Other methods with parameters other than $\tau_c$ could also be used for rapid diagnosis of the damaging potential of an earthquake. For example, Grecksch & Kümpel (1997) investigated whether the initial portion of accelerograms from an earthquake reflects the size of the on-going earthquake using strong-motion accelerograms from 244 earthquakes that occurred in North and Central America. They found that the magnitude of an earthquake can be predicted from the first second of a single accelerogram within $\pm$ 1.36 units. Tsuboi et al. (2002) developed a method to estimate the seismic moment, i.e., magnitude, from the initial portion of ground-motion displacement records. Leach & Dowla (1996) developed a method that uses neural networks to estimate various ground motion parameters from observed ground motion time series. This method analyzes the beginning of three component records of an earthquake and instantaneously provides a profile of impending ground motions. Odaka et al. (2003) developed a method to estimate the epicentral distance and magnitude from a single record using the shape of the envelope function of the initial portion of accelerograms.

Cua & Heaton (2003) (also G. Cua, written communication, 2004) developed a method called the Virtual Seismologist (VS) method, which is a Bayesian approach to seismic early warning. Earthquake seismograms are usually very complex, and judgments of experienced seismologists are often required for interpretation. The VS method emulates how a human seismologist might make inferences regarding magnitude and location given different types of information. The VS method uses ratios of acceleration to displacement of ground motion to obtain constraints on magnitude and envelope attenuation relationships for ground motion velocity to quantify the trade-offs between magnitude and location. It also incorporates background information on seismicity and the magnitude-frequency relationship for the area being monitored. A Bayesian approach can be used to incorporate the background information for interpreting the limited available data from the very beginning. A Bayesian framework would also allow early warning subscribers to make optimal damage-mitigation decisions given the continuously evolving real-time estimates broadcast by the system.

Horiuchi et al. (2004) developed a method that uses *P*-wave arrival times from only a few stations to locate earthquakes within a few seconds. In this method, the information that some stations have not detected *P* wave at the time when an event is detected by other stations is explicitly used. The method has been tested with the NIED's Hi-net data for approximately 500 events.

Because the nucleation and growth of an earthquake are complex, the resulting waveforms are diverse. Some methods may work better than others for identifying certain types of damaging earthquakes, but it may not necessarily work for other types. In other words, no single method is expected to work well for every earthquake. For actual implementation of an EWS, it is desirable to combine as many different methods as possible to make the overall system as robust as possible.

### Hybrid Use of Regional and On-Site Warning Methods

As discussed earlier, the regional warning method using a network of stations is more reliable and can provide more detailed information about the impending ground motion, such as the waveform, spectral content, duration, etc. However, it usually takes time to process the data and has a fairly large "blind zone," the area where the warning cannot be issued in time (e.g., Figure 1). In contrast, the on-site method provides a more rapid warning, thereby reducing the radius of the blind zone, but the information coming from on-site warning is limited to relatively simple parameters. A hybrid use of a regional and on-site warning will enhance the usefulness and reliability of an EWS. Recently Wu & Kanamori (2005) experimented with the $\tau_c$ method for on-site warning using the accelerograph network in Taiwan for which a regional warning system has been already implemented. As shown in Figure 1, the use of an on-site method reduces the radius of the blind zone of the Taiwan Earthquake EWS (Wu & Teng 2002) from 70 to 21 km.

## USE OF EARTHQUAKE EARLY WARNING

As discussed above, the technology of earthquake early warning is developing rapidly. The question is how such early warning information can be used for effective damage mitigation. Several reports have been published (Holden et al. 1989, Shoaf & Bouque 2001) on the implications of earthquake EWSs. Goltz (2003) reports the results of several studies, conducted under the TriNet project, on user needs, warning communication, and public policy issues associated with earthquake early warning. However, very limited experience with such a short-term warning makes it difficult to address this question fully at present.

The potential uses of a few to tens of seconds warning can be discussed both at personal and institutional levels. Personal protective measures that can be undertaken at home and in the workplace include getting under desks and moving away from dangerous chemicals and machinery. During the response to a major earthquake, early warning information can be used to protect clean-up personnel as they work on unstable debris, as was effectively demonstrated by Bakun et al. (1994) after the 1989 Loma Prieta earthquake. Institutional uses of short-term warnings include automated mass-transportation systems that can use a few seconds to slow and stop trains, abort airplane landings, and prevent additional cars from entering the freeway. UrEDAS is a good example applied to the Japanese high-speed train system (Nakamura 1988). Industries can shut down, or initiate the shut down process, of sensitive equipment before peak ground motion arrives, preventing cascading failures. In addition to these immediate uses, the development of an EWS will lead to the development of infrastructure that can utilize the information. For example, construction companies in Japan are developing buildings with semiactive control systems. The buildings can change their mechanical properties within a few seconds to better withstand ground motion (Kobori 2002, Housner et al. 1997). Of course, in actual implementation, the legal implications of false alarms and missed events need to be carefully considered. Also, introduction of an EWS would require multidisciplinary and multiagency cooperation among organizations involved.

Despite these potential difficulties, the technology is improving rapidly with new methods that can be tested within the existing seismic networks. As more new systems are implemented and tested in real time, we will discover novel usage of reliable earthquake early warning information, which will significantly contribute to effective earthquake damage mitigation.



## FUTURE DIRECTIONS AND CONCLUSION

The EWSs developed or implemented so far provide only warnings regarding the severity of impending strong motion. No information regarding the characteristics of the ground motion, either spectrum or time series, is given.

For sophisticated applications, e.g., predictive active structural control, it is obviously desirable for an EWS to provide more detailed information, such as the event mechanism, ground motion spectrum, and time series. Scrivner & Helmberger (1995) explored the possibility of determining the event mechanism using the waveforms from only the stations close to the source of the 1991 Sierra Madre, California, earthquake. They demonstrated that, even with a relatively limited amount of information from the beginning of the waveforms, the mechanism and seismic moment can be estimated fairly accurately. As the data from more distant stations become available, the solution can be updated progressively.

With the recent significant progress in computational methods for wave propagation in three-dimensional (3-D) media, it is now possible to compute realistic waveforms in 3-D media at periods as short as 3 s. Komatitisch et al. (2004) demonstrated that the observed waveforms from regional earthquakes in the Los Angeles basin can be numerically simulated, despite the very complex structures associated with several basins in the area. This success suggests that if all the displacement Green's functions are computed and stored, then once a large event is detected it may be possible to estimate ground motions progressively as the event develops, using the method similar to the one discussed by Scrivner & Helmberger (1995). Further development and testing are necessary to demonstrate the utility of this approach, but the rapid advancement of computational methods suggests that this approach is indeed feasible.

At present, the technology of earthquake early warning is still in progress, but the best way to assess the robustness and utility of new methods is to implement them on an existing system for real-time testing. Large earthquakes are relatively rare and it is important to gain experience with more frequent, smaller earthquakes.

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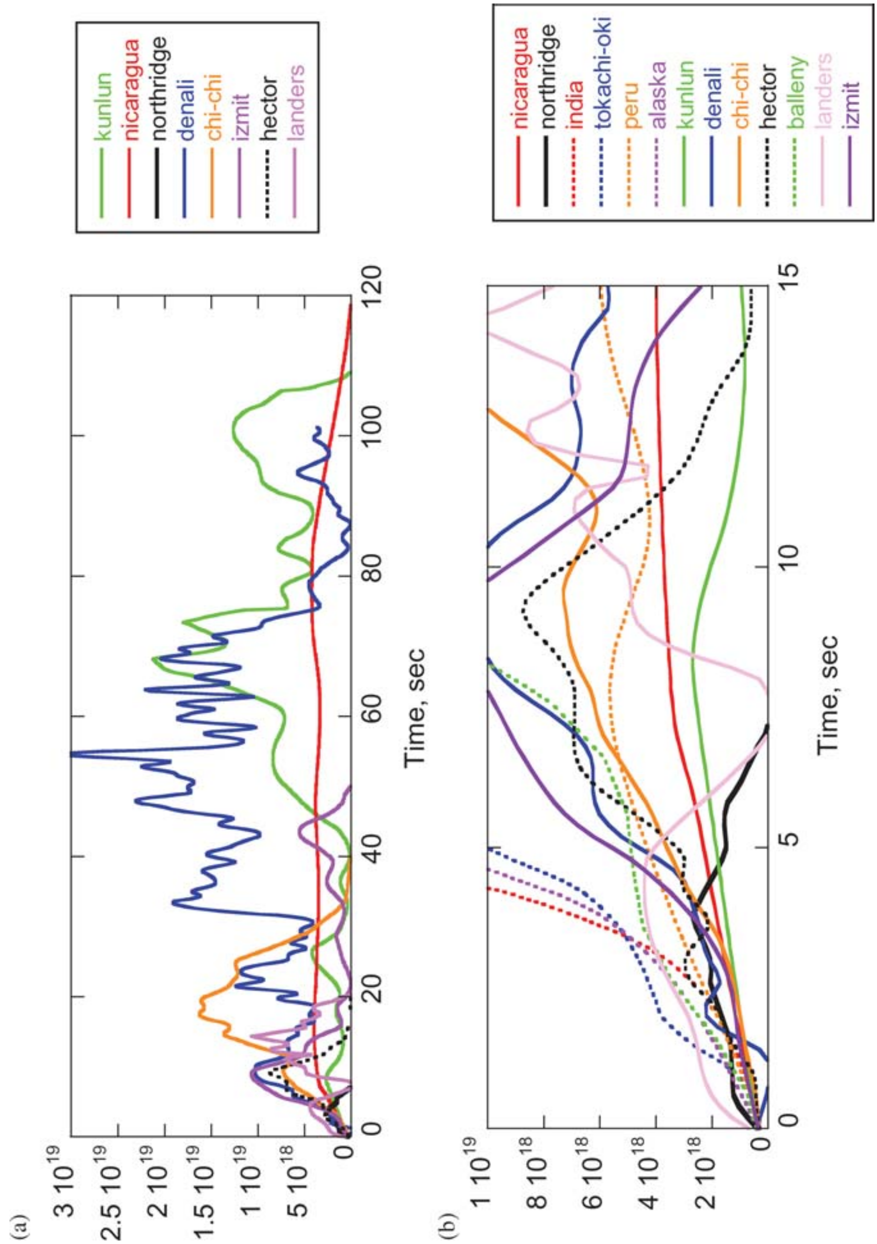


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**Figure 4** (*a*) Moment-rate functions of recent large earthquakes. (*b*) The initial 15 s of the moment-rate functions of large earthquakes. Five more events are added to those shown in (*a*). References for the moment rate functions are 1992 Nicaragua ($M_w$ = 7.6), Kanamori & Kikuchi (1993); 1994 Northridge ($M_w$ = 6.7), Thio & Kanamori (1996); 2001 India ($M_w$ = 7.6) and 2001 Peru ($M_w$ = 8.4), Earthquake Research Institute, University of Tokyo, EIC note in http://wwweic.eri.u-tokyo.ac.jp/EIC/EIC_News/index.html; 2003 Tokachi-Oki, Japan ($M_w$ = 8.3), Yamanaka & Kikuchi (2003); 1994 Alaska ($M_w$ = 9.2), Kikuchi & Fukao (1987) and Kikuchi & Ishida (1993); 2001 Kunlun, China ($M_w$ = 7.8), Lin et al. (2003); 2002 Denali, Alaska ($M_w$ = 7.9), Tsuboi et al. (2003) and C. Ji (written communication, 2003), 1999 Chi-Chi ($M_w$ = 7.6), Ji et al. (2003) and C. Ji (written communication, 2003); 1999 Hector Mine, California ($M_w$ = 7.1), Ji et al. (2002) and C. Ji (written communication, 2003); 1998 Balleny Islands, Antarctica ($M_w$ = 8.1), Henry et al. (2000) and Hjorleifsdottir (written communication, 2003); 1992 Landers, California ($M_w$ = 7.3), Dreger (1994); 1999 Izmit, Turkey ($M_w$ = 7.6), Li et al. (2002).

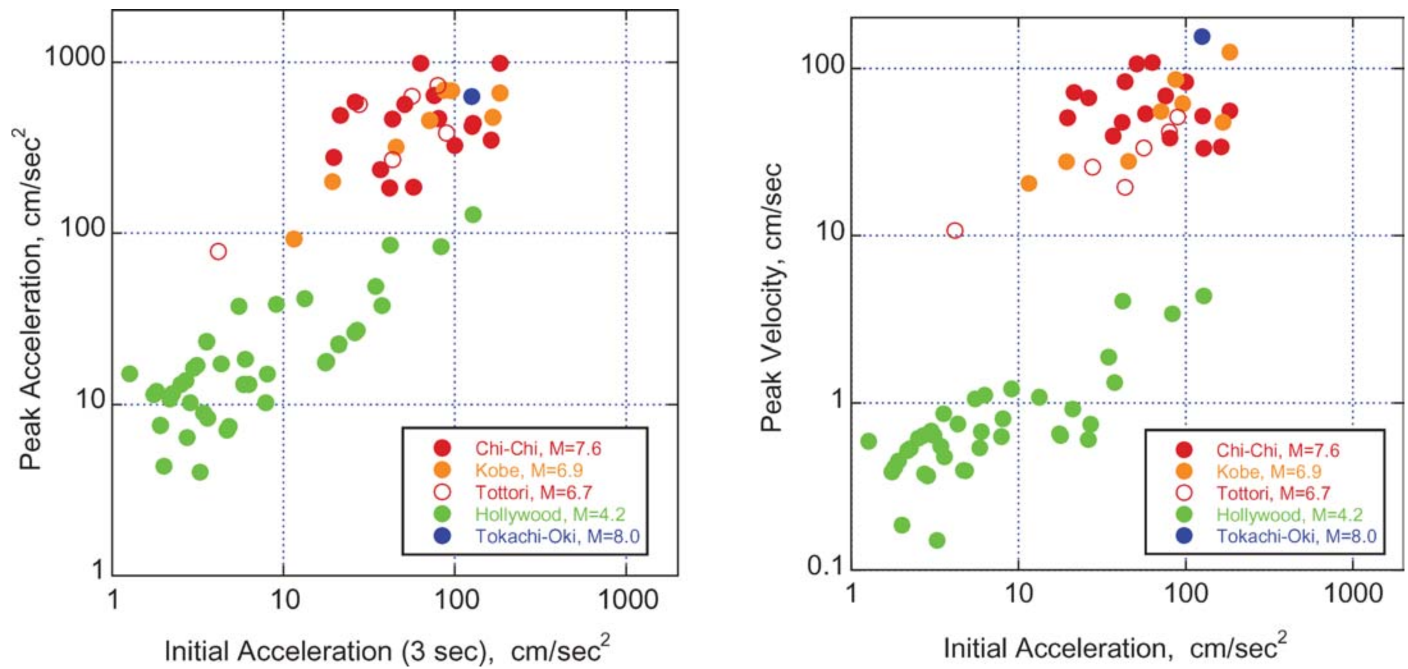


**Figure 7** (*a*) The relationship between the peak ground-motion acceleration (PGA) and the maximum acceleration of the P wave recorded at the same location on the vertical component during the initial 3 s (PK3s). (*b*) A similar relationship between the peak ground-motion velocity (PGV) and PK3s.

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