Earthquake Early Warning and Realtime Earthquake Disaster Prevention

Yutaka Nakamura[1, 2]

Abstract

An *EEW*, *Earthquake Early Warning*, is required to trigger realtime earthquake disaster prevention. However, it is important to avoid too much trust in *EEW* for the disaster prevention. This paper describes the concept of an *EEW* and gives a brief history which eventually led to the development of the *UrEDAS*, the *Urgent Earthquake Detection and Alarm System*, the first operational P-wave early warning system, and its new generation system *FREQL*, *Fast Response Equipment against Quake Load*. A real-world example of disaster prevention by this system is also described. As a specific example to review the effect for the disaster prevention, the leading time by *FREQL* is estimated using the strong motion records of the 2009 L'Aquila earthquake. Finally, the role of information in earthquake disaster prevention will be discussed.

1. Introduction

Obviously, the basic of the earthquake disaster prevention is the strengthening structures and buildings against the earthquake load. The devastations caused by the 2009 L'Aquila earthquake were mainly based on the lack of the strength of the many facilities and structures. It is necessary to escape from the situation as meeting with a large earthquake motion to survive from unexpected damage. The idea to minimize the damage of earthquakes by developing an early warning system was first published by Cooper in 1868 [1] at San Francisco. However, Cooper's idea was never realized and basically forgotten. About 100 years later, another but similar concept of earth-

1 System and Data Research, Tokyo, Japan

2 Tokyo Institute of Technology, Yokohama, Japan

quake warning was published [2] in Japan. At the same time, many institutions and agencies including *JMA*, *Japan Meteorological Agency*, started to research a possible *EEW* based on the existing earthquake observation system. However, there were many problems should be solved.

JNR, *Japanese National Railways*, had also started to research possible EEW based on the same concept as *JMA*, while Nakamura at the *RTRI*, *Railway Technical Research Institute*, of *JNR*, started to develop a different concept in 1979, using only a single station. He completed the prototype *UrEDAS*, pronounced "*Yuredasu*" meaning "*shaking begins*" in Japanese. This was the first actual P-wave detection and alarm system worldwide and was published in Nakamura [3].

Other organizations, such as *JMA*, continued their research and development but without implementing operational systems. This made *JNR* the only agency to implement an operational and functioning actual warning system in the 20th Century.

2. Concept of the *EEW*

There are two kinds of earthquake alarms as illustrated in **Figure 1**. One is the "On-Site Alarm" which is an alarm based on observations close to the objects to be warned. The other one is the "Front Alarm" which is an alarm based on observations near the epicentral area, which is then used for the warning in possible damage areas away from the epicenter. Because the latter alarm concept requires the use of communication networks, it is also sometimes called "Network Alarm". Both alarm types described can make use of two different triggers, also called "alarms". One is the trigger/alarm exceeding a preset level, the so-called "S-wave Alarm" or "Triggered Alarm"; the other one is the trigger/alarm during the preliminary motion, the so-called "P-wave Alarm".

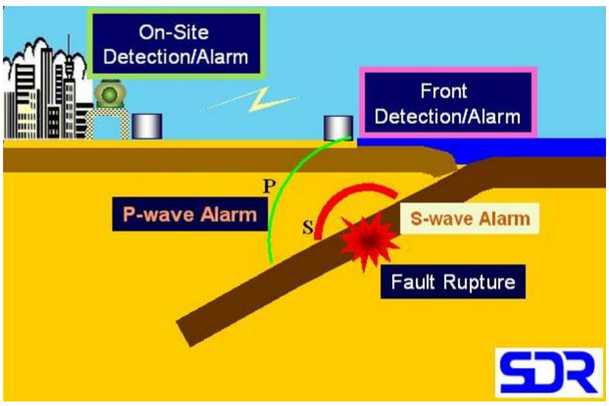

Figure 1. *Concept of the EEW*

3. *EEW* Systems

3.1. *UrEDAS* and *Compact UrEDAS*

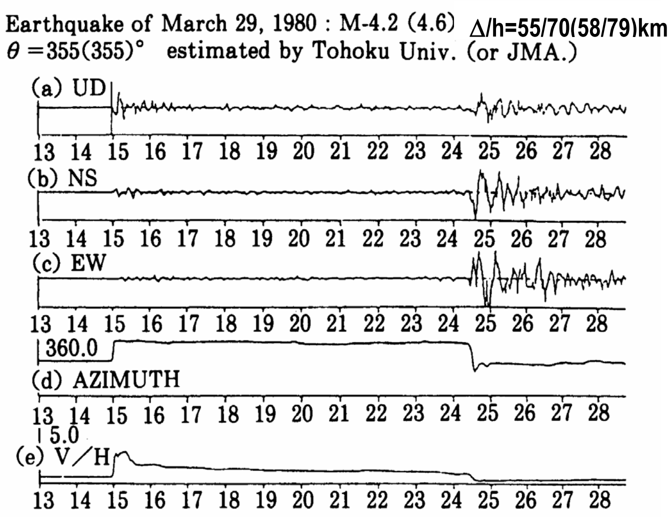

Figure 2. *Example of UrEDAS processing*

Elemental techniques for *UrEDAS* have been established for more than 25 years [3] for a description of individual elemental techniques. The main *UrEDAS* functions are the estimation of magnitude and location, vulnerability assessment and issuing warnings within a few seconds using initial P-wave motion at a single station. Unlike other automatic seismic observation systems, *UrEDAS* does not have to transmit the observed waveform in realtime to a remote processing or centralized system and is therefore comparatively simple. *UrEDAS* calculates parameters such as back azimuth, predominant frequency for magnitude evaluation and vertical to horizontal ratio for discrimination between P and S waves, using the amplitude for each sample in realtime as shown in **Figure 2**. These calculations are processed in realtime without storing waveform data. The amount of processing of *UrEDAS* is almost constant regardless of whether or not an earthquake is occurring, so the number of computational processes does not increase in the event of an earthquake. *UrEDAS* can issue its alarm based on the M-Δ diagram in **Figure 3** immediately after the earthquake detection. The M-Δ diagram is derived

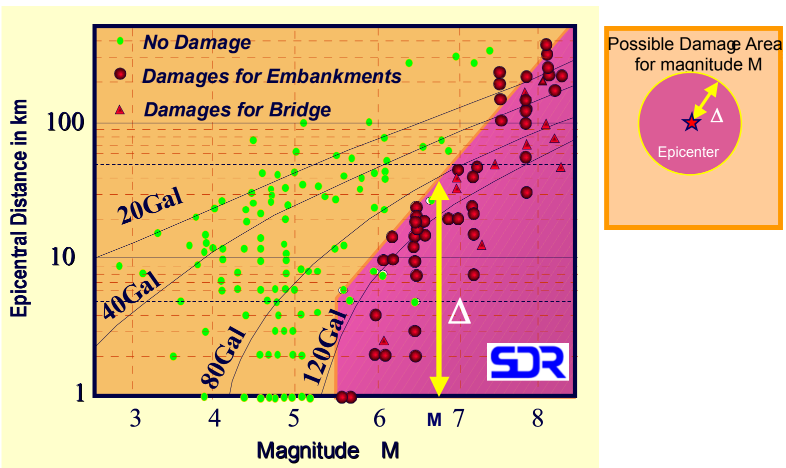

Figure 3. *M-Δ diagram*

from past damage experience to *JNR* facilities and equipment and aids in decreasing the number of false or needless alarms. This kind of alarm is referred to as the M-Δ Alarm. *UrEDAS* can also assist in decisions to safely restart train operations based on the detailed earthquake parameters.

In 1992, *UrEDAS* started routine operations with full functionality for the Tokaido Shinkansen line [4]. These *UrEDAS* issue a P-wave warning with a processing time of just three seconds after detecting the P-wave.

After the 1995 Kobe earthquake, it was recognized that an even shorter warning time would lead to even more effective realtime disaster mitigation. To achieve this, *UrEDAS* was developed further with the aim of being able to issue warnings within about one second after the detection of a damaging earthquake. The resulting system was the *Compact UrEDAS* which became available in 1997 [5] and commenced routine operations for the Tohoku, Joetsu and Nagano Shinkansen lines in 1998.

In contrast to *UrEDAS* which estimates the destructiveness of the earthquake from the earthquake's parameters, *Compact UrEDAS* derives this from the earthquake motion directly 'in realtime' and then issues the alarm, if required. To estimate earthquake dangerousness, the power density *PD* (W/kg) of the earthquake vibration is calculated from the inner product of the acceleration vector $\boldsymbol{a}$ (cm/s^2) and the velocity vector $\boldsymbol{v}$ (cm/s). As this value is a large number, it is normally expressed in terms of the Destructive Intensity (*DI*) defined as the logarithm of absolute value of this inner product (*LPD*, logarithm of the power density) as Eq. (1). The concept of *DI* is illustrated in **Figure 4**.

$$DI = \log|\boldsymbol{a}\cdot\boldsymbol{v}| = LPD + 4.0 \qquad (1)$$

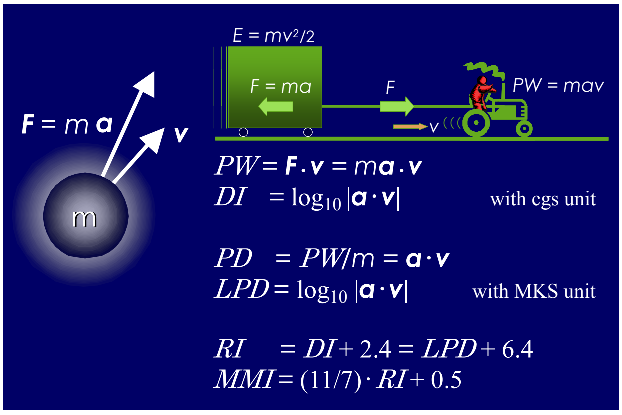

Figure 4. *Earthquake motion indices*

The maximum value of *DI* during an event, *DImax* relates to the earthquake damage and is similar to the instrumental intensity scale of

JMA, I_{JMA}, with the constant difference of 2.4, and corresponds to *MMI*, the Modified Mercalli Intensity. These indices are referred as *RI*, Realtime Intensity, and *MMI*, respectively.

$$RI = DI + 2.4 \quad (2)$$

$$MMI = (11/7)RI + 0.5$$
$$= (11/7)DI + 4.27 \quad (3)$$

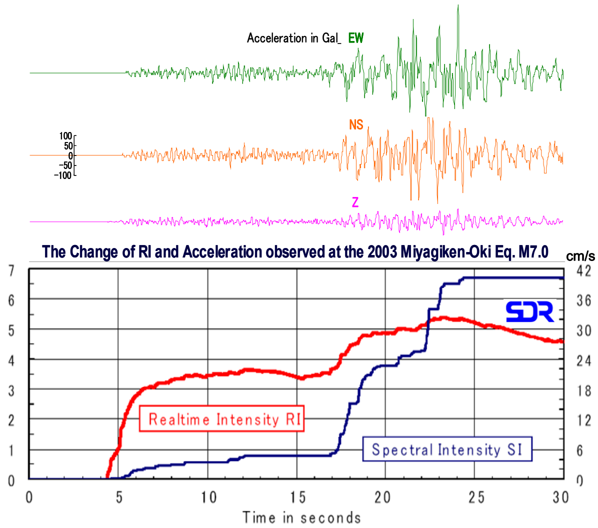

Figure 5. *Acc. waveforms, RI and SI*

I_{JMA} can only be calculated after earthquake termination according to its artificial definition without physical background. Contrary to this, *DI* is defined as the logarithm of Power Density added by a constant. Power Density is a physical variable related closely to earthquake damage. *DI* can be calculated in realtime and its value increases immediately after the P-wave arrival. Because *DI* is sensitive to the P-wave arrival, it can be used to define a P-wave alarm. **Figure 5** shows the change of *RI* as a function of time with the acceleration waveform and the change of *SI*, *Spectral Intensity*. *RI* is more sensitive than both, the acceleration and *SI*, because the value of *RI* increases drastically at the P-wave detection, about one second prior to the other indices.

The function of the *Compact UrEDAS* is to issue an early warning for the area close to the instrument based on the risk of the detected earthquake motion, which is different from the alarm from the *UrEDAS* to the area of possible damage based on the estimated location and magnitude of the detected earthquake. The target area of the *UrEDAS* alarm is about 200km around the location of the instrument, while that of the *Compact UrEDAS* alarm is only about 20km around the instrument. Thus, to maximize the effectiveness of the warning system, an ideal strategy is to use the *UrEDAS* (front alarm or network alarm) to respond to more distant large earthquakes and use the *Compact UrEDAS* (on-site alarm) to respond to nearby earthquakes.

3.2. *FREQL*

As the next step, the functions of *UrEDAS* and *Compact UrEDAS* were combined which not only reduced the size and weight of the system, but also improved its functionality. This development was completed in 2005 and given the name *FREQL*. In Japanese, *FREQL*, pronounced “furekkuru”, means “wave coming”. *FREQL* shortened the processing time required to issue an *UrEDAS*/P-wave alarm - based on the estimated earthquake parameters - from three seconds (for *UrEDAS*) to one second. The previously minimum time for issuing a P-wave alarm based on the dangerousness of the detected earthquake motion by the *Compact UrEDAS* of one second was improved by the *FREQL* to just 0.2 seconds and further to 0.1 seconds in 2009. This enables *FREQL* to issue an alarm before a large earthquake motion even in the case of the epicentral area.

FREQL is not only very valuable in the detection of the initial quake, but is also used during rescue operations after the main shock by detecting, and warning for possible aftershocks. For instance, the Tokyo Fire Department *Hyper Rescue Team* pulled out a small child from underneath debris from a land slide during the 2004 Niigataken-Chuetsu earthquake. After that they had contacted us for using *FREQL* to keep the safety of the rescue staff during the high risk of aftershocks. Based on their request, a portable version of the *FREQL* was developed in 2005, improving the system’s capabilities further and making it more compact. The portable *FREQL* is now in use by many fire departments nationwide, even accompanying international disaster rescue teams, such as to the 2006 Pakistan earthquake and the 2008 Sichuan earthquake, see **Figure 6**. Rescue teams involved in the aftermath of the 2008 Iwate-Miyagi-Nairiku earthquake also benefited greatly from the portable *FREQL*.

Figure 6. *FREQL used by Japanese International Rescue Team at the Sichuan earthquake*

3.3. *Examples of an Integrated System*

Tokyo Metro, a subway network company in the Tokyo metropolitan area, has set up an earthquake early warning system consisting of six *FREQL* stations and an earthquake information system consisting of 33 *AcCo* stations to enable the competent and quick response immediately after an earthquake. *AcCo*, *Acceleration Collector*, is a widely used portable-size alarm seismometer which can display seismic intensity and horizontal acceleration in real-time. The locations of the instruments are shown in **Figure 7** [6]. After setting up *FREQL* and *AcCo* networks, *Tokyo Metro* also installed a receiver for the *JMA's EEW* following instructions from the transportation authority (*JMA* is supervised by this authority). The accurate and quick information from the *FREQL*-based early warning and the *AcCo*-based earthquake information system has helped to minimize the disruption of train operations even in the cases of *JMA's EEW* issuing false or delayed alarms.

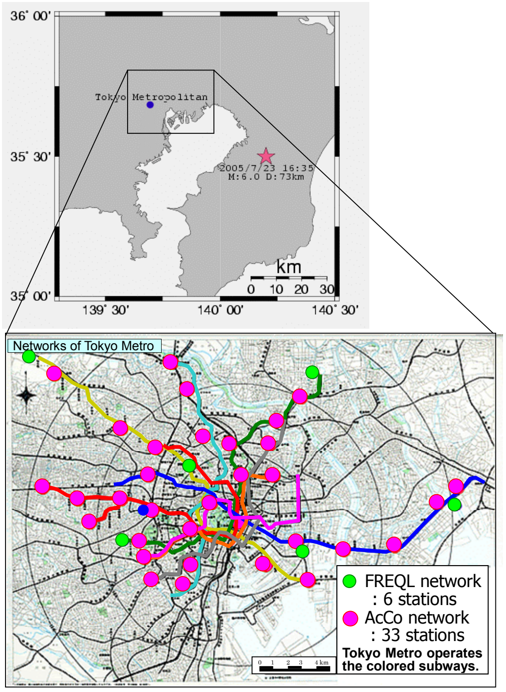

***Figure 7.** EEW and Quick Response (QR) systems of Tokyo Metro*

Additionally, *UrEDAS*-based tsunami warning system [7] has been operated by Wakayama prefecture in Japan. This is the only example in Japan to keep the safety not only relying on the *JMA* information but also monitoring the tsunami independently. **Figure 8** overviews the Kushi-

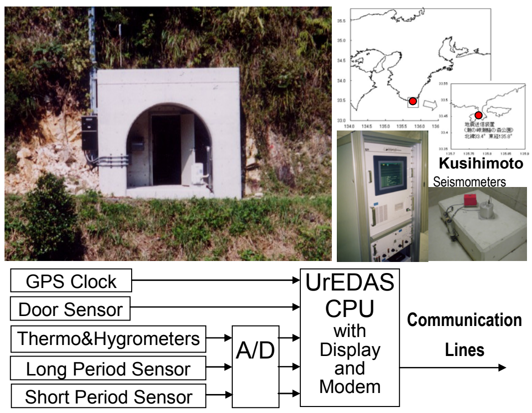

***Figure 8.** Kushimoto UrEDAS for Tsunami Warning, its location and the block diagram of the system*

moto *UrEDAS* observatory installed in March 2000. In September 2004, this system detected two tsunami earthquakes at offshore Kushimoto and reported it three seconds after the detection. Estimated magnitudes were M6.0 and M7.4, and the official magnitudes were M6.9 and M7.4 by *JMA*.

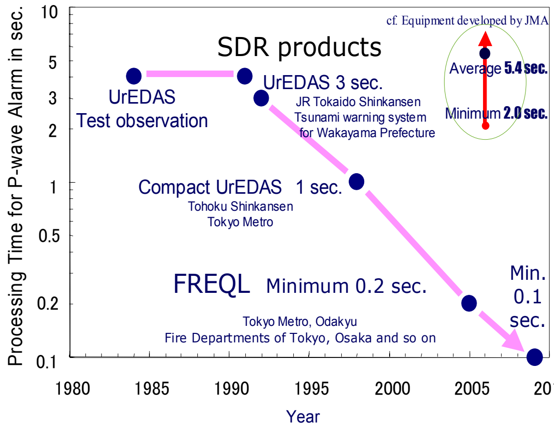

Figure 9. *Processing time of the EEW systems*

Figure 9 shows the timeline for the processing time required by the various warning systems to issue a *P-wave* alarm. It is obvious that *FREQL* exhibits the shortest alarm processing time for all shown *P-wave* detection alarm systems. In addition, it is important to note that *FREQL* simultaneously also calculates and displays *RI*.

4. Example of a Successful Earthquake Early Warning Event

The derailment of the Shinkansen train Toki #325 during the 2004 Niigata-ken Chuetsu earthquake impressively demonstrated the effectiveness and benefits of the early warning system for Shinkansen train operations. The fact that there were no fatalities or injuries to the passengers and crew of the train, totally 155

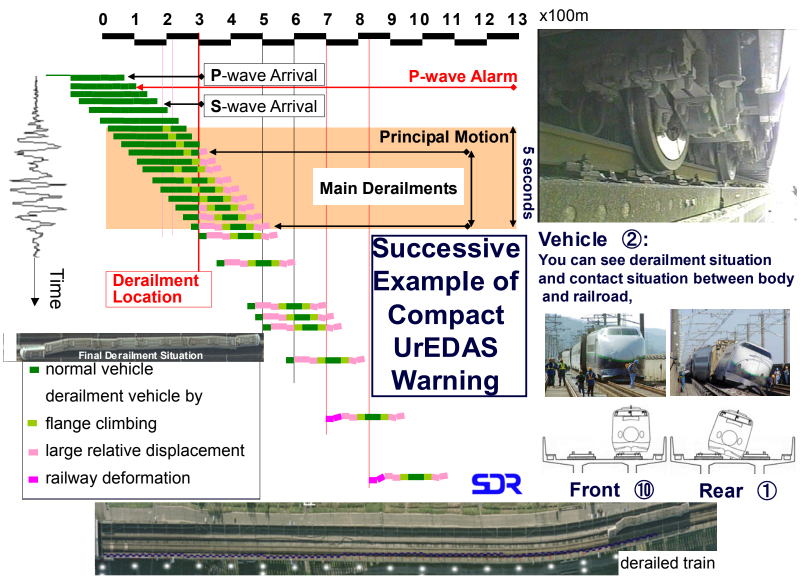

Figure 10. *The Shinkansen derailment during the 2004 Niigata-Ken Chuetsu earthquake*

persons, is clearly a result of the availability of the early warning system. **Figure 10** shows a summary and timeline of the events (see the detail in [8]).

A subsequent simulation of the alarm behaviour of a *FREQL* system using the recorded waveform showed that the train would have received the P-wave alarm another 0.8 seconds earlier, if a *FREQL* had been installed, because the *FREQL* would have issued the P-wave alarm already 0.2 seconds after the P-wave detection.

There are several more examples of successful warnings by *UrEDAS* or *Compact UrEDAS* in 1995, 2003, 2005 and as detailed in [9].

After 2006, *UrEDAS* and *Compact UrEDAS* for Shinkansen lines have been replaced by the *JMA* type system. The reason of replacement is still not clear because the operator explained that the replacement aimed to make the alarm faster but the new system had not been earlier than *UrEDAS* or *Compact UrEDAS* even now.

5. Leading Time by *FREQL* Simulated with Strong Motion Records

In this section, a simulated *EEW* of *FREQL* during an earthquake is described and compared to the actual performance of *JMA's EEW*, based on the observed data.

JMA's system for *EEW* had been developed since around 2000 and officially operated in November 2007 [10].This system is so called an intermittent processing system, so the system determines the necessary parameters by fitting a function with stored waveform data. According to *JMA*, the duration of the stored data is required at least two seconds and averaged process time is 5.4 seconds. The parameters of each observation site are gathered in *JMA*'s centralized system, and then processed again. After this proc-

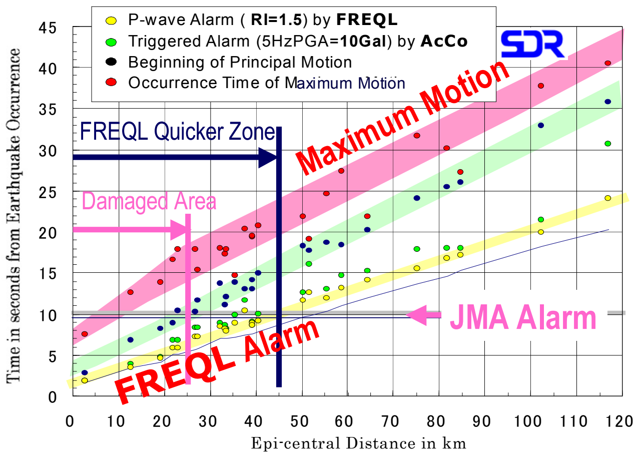

Figure 11. *EEW timing for the 2008 Iwate-Miyagi-Nairiku earthquake*

ess, a warning is issued if necessary.

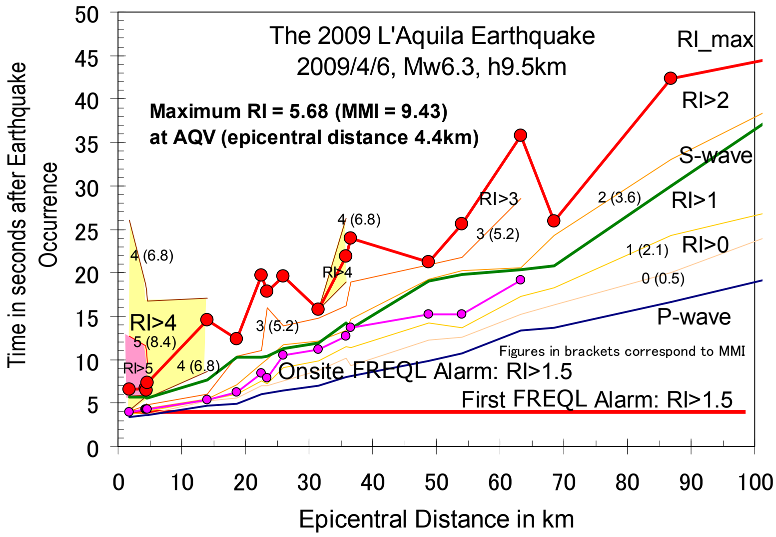

Figure 12. *EEW timing for the 2009 L'Aquila Eq.*

The 2008 Iwate-Miyagi-Nairiku earthquake caused severe damage in the epicentral area, yet *JMA's EEW* system was unable to issue an alarm before the start of shaking in the damaged area within approximately 25km of the epicentre. **Figure 11** shows the time of the actual alarms issued by *JMA's EEW* and compares them with alarms which an on-site *FREQL* system would have been able to issue, based on a simulation using the recorded waveforms. The depth of this earthquake was approximately 8km below the surface. The alarm from *JMA's EEW* was issued 3.5 seconds after the event detection to the primary customer and one second later to the public, which is equivalent to about 10 seconds after the earthquake occurrence. Although the timing of the alarm in this case was faster than the averaged processing time of 5.4 seconds (see **Figure 9**), the warning was still only delivered after the beginning of the strong motion. In contrast to this, *FREQL* is expected to issue an alarm 0.2 seconds after the *P-wave* detection in the damaged area, i.e. the time margin before the beginning of the strong motion is several seconds, even at the epicentre itself.

Until today, there has been no example where *JMA's EEW* was able to effectively be used for disaster prevention by means of early warning.

Figure 12 shows a result of simulation for the 2009 L'Aquila earthquake using strong motion records [11]. According to this figure, *FREQL* was expected to get a few seconds as a leading time at even epicentral area. It is very short time, but during the leading time people could be evacuate into some sturdy desk before falling down the floor or the ceiling. Of course it is needless to say that the most important measure is to build the structures enough earthquake-proof. Even after the reinforcement against the earthquake, because there is still risk on the falling objects, the repeated emergency drills are essential to acquire the image of the damage situation after the earthquake for the reasonable countermeasures. Anyway there is no system to issue the earthquake alarm quicker than on-site *FREQL*, so it is advisable to take proper countermeasures without exaggerating the effect of *EEW*.

6. What Information is required for Earthquake Disaster Mitigation?

From the operational side, there are three pieces of information relevant to realtime earthquake assessment:

(1) An early warning before the onset of the strong shaking for the area of certain damage,

(2) Information before the shaking starts about the area that will not be damaged, and

(3) A precise and detailed estimate of the location and extent of the area where serious damage can be expected.

The most important issue for public agencies is to have a reliable assessment as listed in Item (3) above, so that rescue activities in the damaged areas can be initiated immediately. For the public agencies it is impossible to deliver information as under Item (1) due to the long processing and communication times. Only on-site early warnings can deliver that information. In general, the early warning can only be used to trigger individual or locally based social group help or action. Governmental assistance will mainly focus on the rescue work in the seriously damaged areas evaluated by information as under Item (3). Information as under Item (2) has no relevance to damage, and is unnecessary information for disaster prevention. For most events, unfortunately, *JMA's EEW* seems usually only capable to deliver information as under Item (2).

It is important to receive rapid and accurate earthquake information from organizations such as *JMA* in Japan, but it is also important not to restrict the delivery of the information as under Item (3) from other organizations, such as local universities or institutions.

For the most appropriate and quick response after the earthquake, the "actual observed" seismic motion as intensity, not an estimated value, is the most important information because the degree of damage can be estimated from it.

It became very obvious that an M7 class earthquake causes catastrophic damage especially in the area close to the epicentre. Although M7 class earthquakes are quite common in Japan, it is a potentially fatal flaw in the warning system that the *JMA's EEW* cannot issue a timely and accurate estimate of the large motion in the catastrophically damaged area.

For M8 class events (which occur statistically once every several tens of years in Japan), the *JMA's EEW* seems to be capable to issue a warning with a useful time margin for the strong motion. Yet such a warning is only useful, if it is readily available for the damaged area more than 50 km from the epicentre. This, however, might not be the case, because in such a serious situation it is quite possible that the information is lost or delayed by problems in the communication system.

On-site alarm equipment such as the *FREQL*, is capable to issue the alarm in as short a time as 0.1 seconds after the P-wave and can thus issue the warning before the onset of the large earthquake motion, even for locations close to the epicentre. If then a local FM radio station would broadcast the *FREQL* information, there would be a time margin for preventative action within the damaged area.

7. Concluding Remarks

Realtime earthquake warning was initially aimed at disaster prevention for the train system in Japan, but is by now used in many other environments as well. To be of wide-ranging benefit, the time margin of the warning must be very short on a time scale of seconds to enable quick action by the general public, such as to seek shelter (like under a sturdy desk) or to evacuate immediately to a pre-determined safety zone.

It is clear that the primary preventative action by the people at the time of the earthquake is to keep away from places where they could be hit by falling or loose objects. To be able to do this obviously requires a timely and immediate warning to be issued.

A warning cannot prevent the possible collapse of structures, but it can most definitely assist people evacuating from collapsing facilities. National organizations should be able to specify the area of expected catastrophic damage accurately and initiate rescue operations without delay based on information from responsible and capable organizations in realtime.

Acknowledgment

The author wish to thank *Tokyo Metro* and the *Tokyo Fire Department* for their cooperation in the implementation the systems: *FREQL*-based early warning system and *AcCo*-based earthquake information system. The simulation described in this article partially used the waveform data from K-NET and KiK-net of *NIED*, *National Institute of Earth Science for Disaster Prevention*, and from ItacaNet [11]. I would like to express my sincere thanks to Mr. J. Saita and Mr. T. Sato, the senior research engineers of *SDR*, *System and Data Research*, and all individuals that contributed to this paper.

References

[1] J. D. Cooper, Earthquake indicator, San Francisco Daily Evening Bulletin, 3rd November 1868.

[2] M. Hakuno, H. Takahashi, Earthquake warning system 10 seconds before the strong motion (in Japanese), Shizen, September 1972.

[3] Y. Nakamura, On the urgent earthquake detection and alarm system (UrEDAS), Proceedings of 9th World Conference on Earthquake Engineering (WCEE), Vol. VIII, 1988, pp.673-678.

[4] Y. Nakamura, Real-time information systems for hazards mitigation, Proceedings of 11th WCEE, 1996.

[5] Y. Nakamura, A new concept for the earthquake vulnerability estimation and its application to the early warning system, in: J. Zschau et al. (Eds.), Early warning Systems for Natural Disaster Reduction, Springer, 2003 (presented at EWC'98, 1998), pp. 693-699.

[6] Y. Nakamura, J. Saita, FREQL and AcCo for a Quick Response to Earthquake, in: P. Gasparini et al. (Eds.), Earthquake Early Warning Systems, Springer, 2007, pp. 308-324.

[7] J. Saita, Y. Nakamura, UrEDAS: The Early Warning System for Mitigation of Disasters Caused by Earthquakes and Tsunamis, in: J. Zschau et al. (Eds.), Early warning Systems for Natural Disaster Reduction, Springer, 2003 (presented at EWC'98, 1998), pp. 453-460.

[8] Y. Nakamura, J. Saita, T. Sato, On an earthquake early system (EEW) and its applications, Soil Dynamics and Earthquake Engineering, 2010, doi:10.1016/j.solidyn.2010.04.012.

[9] Y. Nakamura, J. Saita, UrEDAS, the Earthquake Warning System: Today and Tomorrow, in: P. Gasparini et al. (Eds.), Earthquake Early Warning Systems, Springer, 2007, pp. 249-281.

[10] Doi, K., Earthquake Early warning-Provision to General Public and Future Prospect-, Proc. of 14th WCEE, S05-03-017, 2008.

[11] Data source of strong ground motion records of the 2009 L'Aquila earthquake: http://itaca.mi.ingv.it/ItacaNet/