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ON-SITE ALARM – THE EFFECTIVE EARTHQUAKE EARLY WARNING

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Abstract: The most important countermeasure against earthquake risk is to have all structures strong enough for the possible earthquake load. In this regard, an early warning system should be installed to reduce the possibility of earthquake disaster. An early warning system is required mainly to issue an alarm to have a time margin for evacuating or shutting down key facilities, and not to determine exact earthquake parameters. Thus the early warning system must be realized independently with On-Site alarm and the government and other public authorities must release accurate earthquake information immediately after the earthquake.

1. INTRODUCTION

There are two kinds of the earthquake alarm as in Fig.1. One is "On-Site Alarm" which is the alarm based on the observation at the side of the objects to be warned. The other is "Front Alarm" which is the alarm based on the observation near the epicentral area for the warning to possible damaged area. "Front Alarm" is transmitted by using communication networks, so the alarm is also called as "Network Alarm".

For each, there are two more kinds of alarm. One is the alarm exceeding the preset level, so-called "S-wave Alarm" or "Triggered Alarm". And the other one is the alarm during the preliminary motion, so-called "P-wave Alarm".

As the first stage of the earthquake alarm, the simple triggered alarm had been realized. This is the alarm seismometer observing the strong motion just near the objective for the alarm, and when the earthquake motion exceeds the preset level, the alarm seismometer issues the alarm. Although because of the anxiety of false alarm, it is not able to set the alarm level low and the alarm is issued almost same time to the severe strong motion, it is useful to stop the gas supply or other systems automatically.

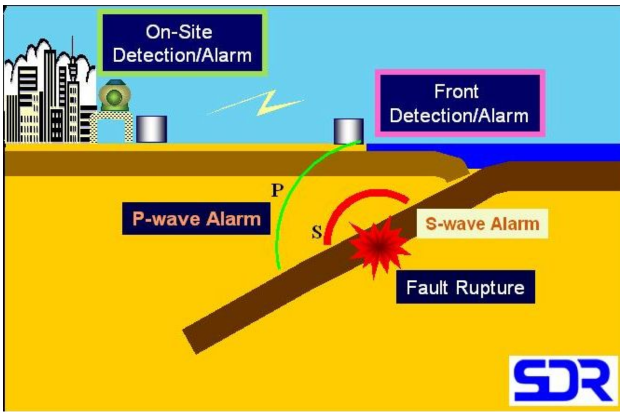


Fig.1 Comcept of Earthquake Early Warning

Next, to extend the margin time before the strong motion arrival, it was considered the way to observe the earthquake near the focal area, so-called "Front Alarm". This idea originally had been offered in 1868 by Dr. Cooper. He proposed to utilize the propagation time of the earthquake motion from the epicenter to alarmed area and support the activities for escape. More than 100 years after this original idea, the first system realizing the "Front Alarm" was developed as the coast line detection system for Tohoku Shinkansen line in 1982. After this, SAS, Sistema de Alerta Sísmica, for Mexico City started operation in 1991.

Then the next system was considered to detect the initial part of the earthquake motion and issue the alarm based on the risk of the earthquake. The first P wave detection system for practical use, UrEDAS, Urgent Earthquake Detection and Alarm System, was realized as the front alarm system for Tokaido Shinkansen line in 1992, and then almost same system was installed for Sanyo Shinkansen line in 1996.

The 1995 Great Hanshin Disaster triggered to develop earlier P wave alarm system because of the impression of necessity to make on-site P wave alarm. This is Compact UrEDAS and it was installed for Tohoku, Joetsu and Nagano Shinkansen lines and Tokyo metro subway network.

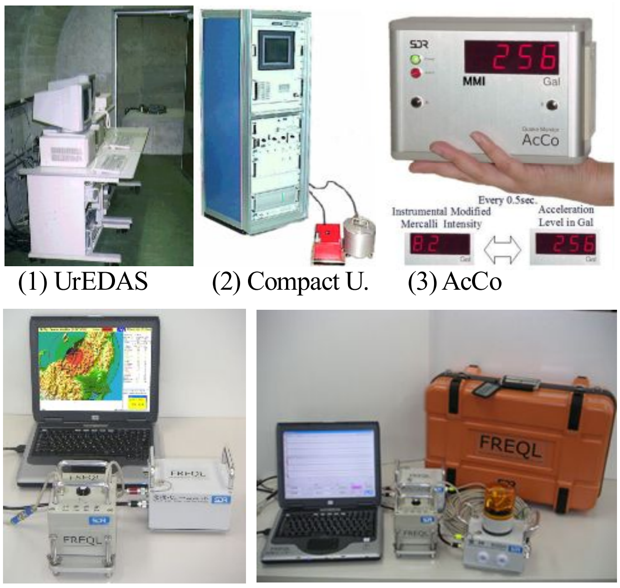
And then Wakayama prefecture decided to install UrEDAS for their own tsunami disaster prevention system and started test operation in 2000.

As the new generation of UrEDAS and Compact UrEDAS, the new small-sized instrument FREQL, Fast Response Equipment against Quake Load, is developed to shorten the processing time for alarm and to combine the functions of UrEDAS and Compact UrEDAS. After P wave detection, FREQL can issue the alarm within one second (minimum in 0.2 seconds) and estimate the earthquake parameters at one second. Since 2005, FREQL has been adopted for the hyper rescue team of Tokyo fire department to save the staffs from the large after shocks during their activity. The hyper rescue teams are famous of the salvage of the child from the land slide after the 2004 Niigataken Chuetsu Earthquake, and they were afraid of the hazard caused by the aftershocks at that time.

On the other hand, it is necessary for local facilities to grasp immediately their “own” strong motion index for the quick response. For this purpose, a simple seismometer “AcCo”, Acceleration Collector, was developed. This unique palmtop seismometer has a bright indicator, memory and alarm buzzer and relay connecter.

On-Site alarm is more important than network alarm, because network alarm is sometime missed during data communication. From the view of this, it is not enough to receive the Earthquake Early Information from JMA, Japan Meteorological Agency, EEI. Contrary with this, FREQL has both functions of UrEDAS and Compact UrEDAS for On-Site Alarm and Network Alarm. And also AcCo has simple alarm functions for On-Site Alarm.

Fig.2 shows systems of EEW: UrEDAS, Compact UrEDAS, FREQL and AcCo.



(1) UrEDAS (2) Compact U. (3) AcCo

(4) FREQL (5) FREQL of Portable Type

Fig.2 UrEDAS, Compact UrEDAS, FREQL and AcCo

2. Principal EEW: UrEDAS, Compact UrEDAS and FREQL

2.1 UrEDAS

Main UrEDAS functions are estimation of magnitude and location, vulnerability assessment and warning within a few seconds of initial P wave motion at a single station. Unlike the existing automatic seismic observation systems, UrEDAS does not have to transmit the observed waveform in real time to a remote processing or centralized system and thus the system can be considerably simplified.

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 amplitude level for each sampling in real time. These calculations are basically processed in real time without storing waveform data. UrEDAS processes these calculation continuously regardless of whether or not an earthquake occurs, and calculates just like filtering, so the number of procedures is not increased in the event of an earthquake. UrEDAS can detect earthquakes in P-wave triggering with the amplitude level, and then estimates earthquake parameters such as magnitude, epicentral and hypocentral distance, depth and back azimuth from the result of real-time calculation in a fixed period. UrEDAS can issue an alarm based on the M-Δ diagram as in Fig.3 immediately after earthquake detection. This new way of alarm is referred to as the M-Δ Alarm. Moreover UrEDAS can support restarting operation based on the detailed earthquake parameters.

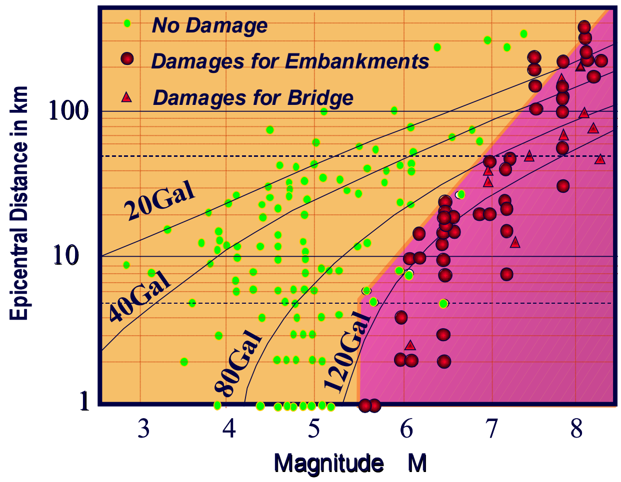


Fig.3 M-Δ Diagram

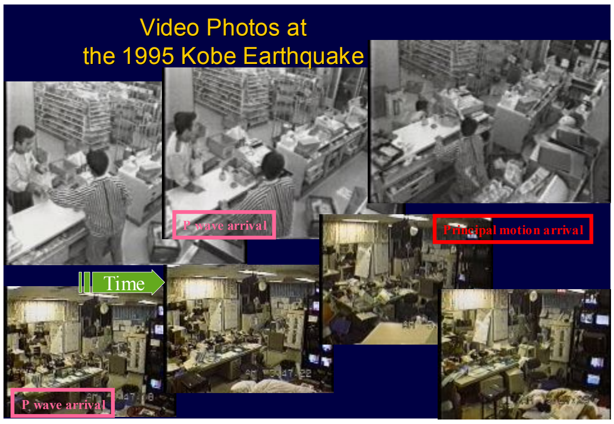


Fig.4 Video Photos examples at focal region

The 1995 Hyogoken-Nanbu Earthquake also provided the motivation for Compact-UrEDAS development. Fig.4 shows several pictures from the VTR shoot in the focal region, initial P-wave motion was detected as something happening, and then severe motion started. In an interview with victims, although there were only a few seconds between detection of something happening to earthquake recognition, there was anxiety and fear because they could not understand what was happening during this period and felt relieved after recognition of earthquake occurrence. To counter this kind of feeling, earlier earthquake alarm was required: Compact UrEDAS was developed to issue the alarm within one second of P-wave arrival.

2.2 Compact UrEDAS

Compact UrEDAS estimates the expected destructiveness of the earthquake immediately from the earthquake motion directly, not from the earthquake parameters as UrEDAS, and then issues the alarm if needed. To estimate earthquake dangerousness, the power of the earthquake motion is calculated from the inner product of acceleration vector and velocity vector, but this value will be large. Hence Destructive Intensity (DI) is defined as the logarithm of absolute value of this inner product as in Fig. 5.

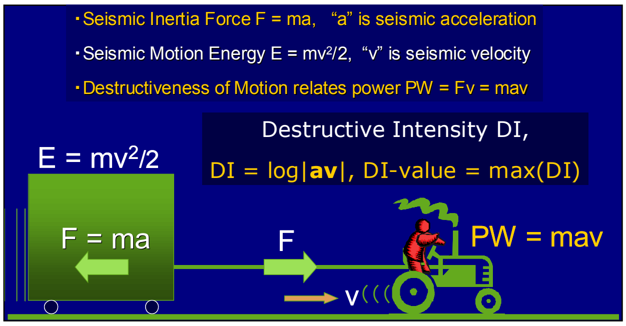


Fig.5 Definition of DI

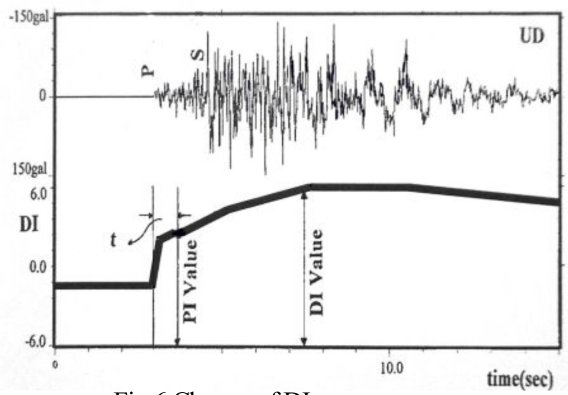


Fig.6 Change of DI

Fig. 6 shows the change of DI as a function of time. When the P wave arrives, DI increases drastically. PI value is defined as maximum DI within t seconds after P-wave detection. This value is suggested to be used for P-wave alarm. Subsequently, DI continues to increase slowly until the S-wave arrival, after which it reaches its maximum value which is called the DI value. This value relates to earthquake damage and is similar to the Instrumental Intensity scale of JMA or MMI, Modified Mercalli Intensity. Instrumental JMA seismic intensity can be determined only after the earthquake has terminated. On the other hand, DI has a very important practical advantage, because it can be calculated in real time soon after the P-wave arrival with physical meaning. In other words, with the continuous observations of DI, an earthquake alarm can be issued efficiently and damage can be estimated precisely.

2.3 FREQL

FREQL is integrated the functions of UrEDAS, Compact UrEDAS and AcCo. Which is to say that FREQL can estimate the earthquake parameters one second after the P wave detection faster than UrEDAS, can judge the dangerousness of the earthquake motion within one second, minimum in 0.2 seconds, after P wave detection faster than Compact UrEDAS, and can output the information and alarm based on both acceleration and RI, Realtime Intensity, in real time same as AcCo.

And the all components of seismometer, sensors, A/D converter, amplifier, CPU and so on, are put together in small aluminum die-cast vessel of almost 5 inches cube, and the system is electrical isolated. So the FREQL is easy to install and the structure of FREQL is noise proof.

FREQL also has functions to omit the influence of electrical thunder noise and to detect the P wave after rather small pre-shock. Thus it is able to say that FREQL solved the known problems of the ordinary earthquake early warning systems. It is known that there was a pre-shock at the time of the 1994 Northridge earthquake attacked Los Angels and the 1995 Hyogoken-Nanbu Earthquake attacked great Hanshin area. It seems to be failing for the early warning system except FREQL that it is not possible to issue the alarm for large earthquake motion if the pre-shock exists just before the destructive earthquake because the pre-shock is recognized as small event. And also it seems to be difficult for the huge system to keep running perfectly under the destructive earthquake motion. It is uncertain only with such remote systems because of information lack. It must be considered on installing the onsite warning system for the important facility.

FREQL is toward to the new field for the early warning system, as for the hyper rescue teams of Tokyo fire department under the severe situation with the risk of aftershocks (see Fig. 7).

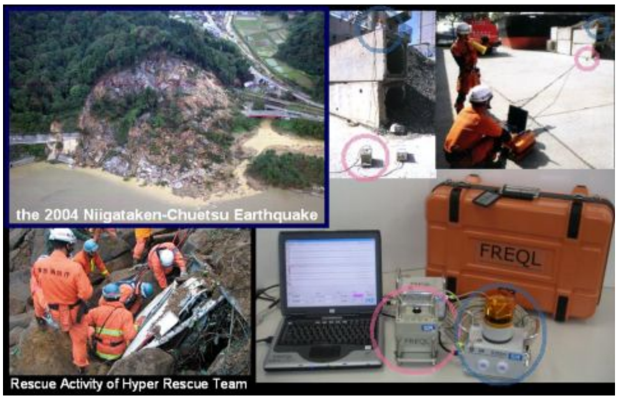


Fig.7 New Field for EEW

Hyper rescue teams made a miraculous activity but the activity was always in a risk of large after shocks. After the activity at the damaged area of the 2004 Niigataken-Chuetsu Earthquake, the Tokyo fire department approached us to adopt FREQL as a support system for the rescue activity, taking notice of the portability, rapidness and accuracy of the warning. FREQL for Tokyo fire department was consists of FREQL main body, power unit with backup battery for three hours, central monitoring system and the portable alarm instrument with more than 105dB loud alarm and rotary light.

Tokyo fire department has equipped the FREQL unit form spring of 2005, and since 2007, three hyper rescue teams is operating. At the time of their rescue activity after the 2005 Pakistan earthquake, they reported that FREQL works in right manner. Now, there are many FREQL of portable type equipped at local fire stations in Japan.

And the FREQL of permanent type are used in many field such as subway, nuclear power plant, high-rise building, semiconductor facilities, and etc., in Japan.

Now, in Berkeley and in Pasadena, FREQL has started test observation. These projects are doing under the support by UC Berkeley and Caltech. I hope this FREQL network growth to Pan-Pacific Tsunami Warning System.

2.4 AcCo

Because usual seismometers were expensive and required an expert of installation and maintenance, so they were installed for limited facilities. After the Kobe earthquake, the number of seismometer was increased but at most thousands sets for whole Japan. It is not so much because it means one set per several tens km^2 or per several ten thousands person. Even so there are many seismometers in Japan, but many hazardous countries have only a few seismometers. So it is difficult to take exact countermeasure against earthquake disasters because it is impossible to grasp and analysis the damage based on the strong motion records and to draw a plan of the city with certain strategy.

AcCo was developed to realize a simple seismometer to issue alarm and record the strong motion in low cost. Since AcCo is just a palmtop size instrument, it can indicate not only acceleration but also the world's first real time intensity. So AcCo can issue alarm with the trigger of both acceleration and intensity.

AcCo indicates acceleration and intensity if the 5HzPGA (5 Hz low passed peak ground acceleration) exceeds 5 Gals as in Fig.2(3). Intensity can be chose from RI, MMI or PEIS, Philippine Earthquake Intensity Scale. AcCo can output the digitized waveform via serial port and also record the waveform for the two largest events with delay memory. AcCo can work with AC power supply and backup battery for seven hours.

Because AcCo indicates acceleration as inertial force and RI as the power of the earthquake motion, it is useful to learn the sense for the meaning of acceleration and intensity from the experience. This sense is required for the exact image against the earthquake motion.

AcCo is applied for many fields as warning system, education, kindergarden, factory, train operation and so on. And also AcCo is used not only in Japan but also in out side of Japan for a instance, Taiwan, Philippine and etc..

2.5. Alarm timing and margin time gained by EEW

In case of the system requiring the earlier warning with no error or accidental warning, it is necessary to install a system with high reliability and sophisticated as FREQL. But in general, it seems to be useful even the simple warning system in general. This kind of system seems to be useful enough in many cases under the situation of several alarms per year even in higher seismic activity area of Japan. AcCo 10 Gals alarm or RI 2.0 alarm can play the role of this simple early warning. Fig.8 shows the relationship example between the alarm timings. Since the AcCo 10 Gals alarm or RI 2.0 alarm is a little later than the P wave alarm of FREQL, it is enough earlier than the ordinary triggered S wave alarm.

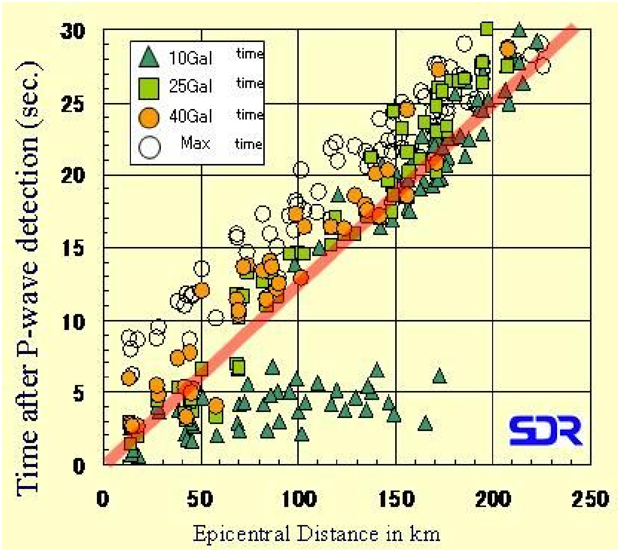
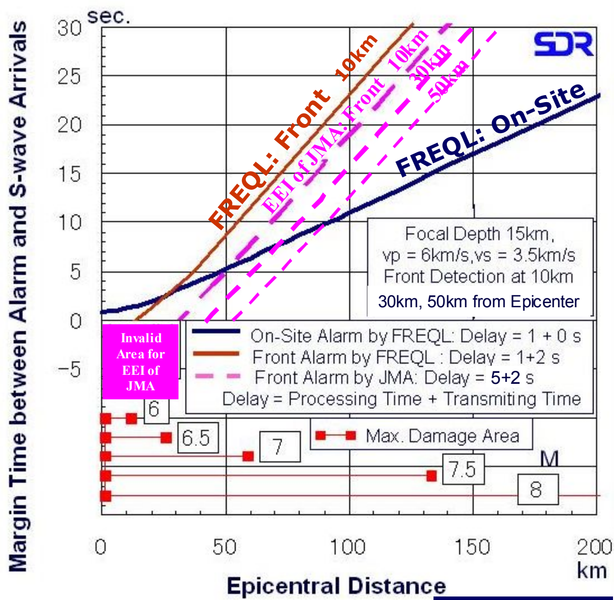


Fig.8 An example of alarm timings by simple triggers in case of the 2000 Tottoriken-Seibu Earthquake



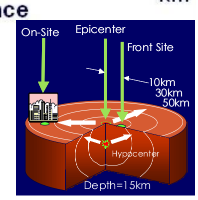


Fig.9 Margin time by EEW

Fig.9 shows gained margin time by EEW. Basic condition for calculating margin time is assumed as follows: focal depth is15km, velocity of P-wave and S-wave are vp = 6 km/s and vs = 3.5 km/s, respectively, front detection site at 10 km, 30 km and 50 km from the epicenter.

Based on the calculation for 10km, EEI of JMA comes after S wave arrival within a 30 km radius as confession by JMA. On-Site alarm by FREQL can keep at least more than one second even just above the epicenter; and more margin time than front alarm by JMA within about 55 km radius from the epicenter. This distance corresponds for out line of the damage area for over M7. It means that the EEI of JMA is not available the estimated damaged area up to M7, so it seems that it is not useful for the recent Japanese earthquake in this 20 years. Contrary to this, the on-site FREQL alarm is available even around the focal area; of course the margin time is just a few seconds. So we should take a hard look at the on-site alarm and put it into practical use. It is also useful for popularization of earthquake disaster mitigation. It seems that there are many fields not so effected by false alarm if reset easily. Official information as correct location and magnitude must be informed within few minutes for the exact clear of the alarm. And this kind of information must keep suitable redundancy so there must be informed from several organizations.

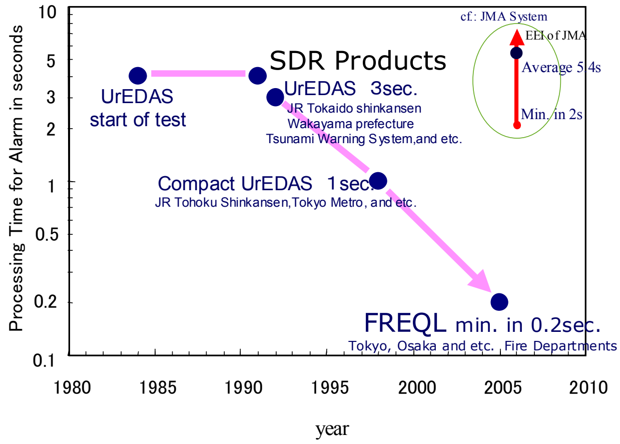


Fig.10 Change of processing time for EEW

3. Practical Operation Example of Compact UrEDAS

At the time of the 2004 Niigataken Chuetsu Earthquake, Mjma 6.8, there were four trains running in the focal area. There are four observatories called Oshikiri SP, Nagaoka SSP, Kawaguchi SS and Muikamachi SP, from north to south. Of these stations, Kawaguchi and Nagaoka issued both the P-wave and the S-wave alarms, and the others issued only the S-wave alarm. Every station issued the alarm for the section to the next station (see Fig.11). At first Kawaguchi and then Nagaoka issued the P-wave alarm. Subsequently, Oshikiri and Muikamachi issued the 40 Gals alarm. As the result, trains Toki #325 and #332 received the alarm 3.6 seconds after the earthquake occurred, Toki #406 4.5 seconds after and Toki #361 11.2 seconds. The

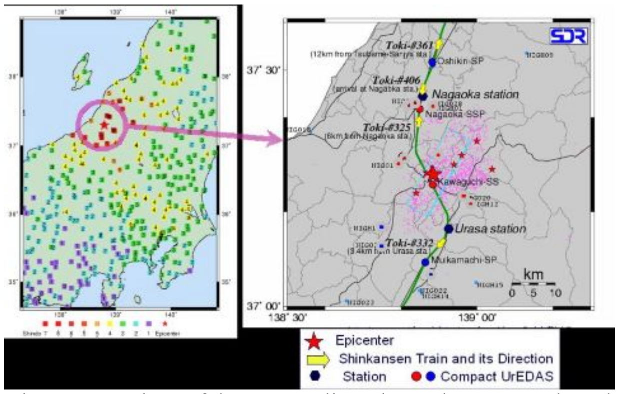


Fig.11 Overview of the 2004 Niigataken-Chuetsu Earthquake

section damaged was between Muikamachi and Nagaoka. Trains traveling on this section received the alarm immediately, proving that the alarm system settings were appropriate.

The UD component of earthquake motion predominate the high frequency more than 10 Hz. The Shinkansen line runs from north to south and the EW component seems to effect derailment. In the case of the EW component, there is a peak at 1.5 Hz and the range of 1 to 2.5 Hz predominates. The natural frequency of the Shinkansen vehicle is included this frequency range.

The Kawaguchi observatory detected the P wave 2.6 seconds after the earthquake occurred, and one second after that, or 3.6 seconds after the event, issued a P-wave alarm. When the derailed train, Toki #325, encountered the earthquake motion when traveling at 75 m from the Takiya tunnel exit of 206km000m, it was three seconds after earthquake occurrence. 3.6 seconds after the earthquake, the train received the alarm from the Compact UrEDAS and the power supply was interrupted. The Shinkansen train situated automatically to apply the break immediately at the interruption of power supply. The driver put on the emergency brake after recognizing the Compact UrEDAS alarm. The S-wave hit the train 2.5 seconds after the alarm, and more one second later, a strong motion with five seconds duration hit the train. Fig.12 shows the schematic

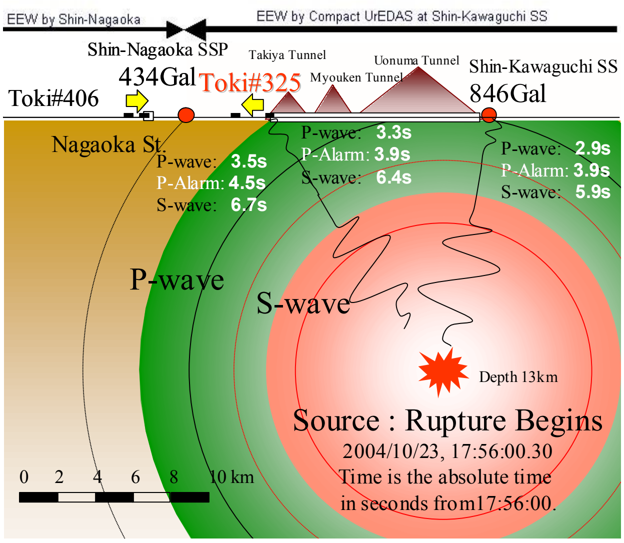


Fig.12 Schematic diagram for this earthquake

diagram for this earthquake.

As the result of simulation using the strong-motion records at Kawaguchi and Nagaoka, real-time intensity (RI) rose sharply with the earthquake motion arrival and immediately reached the P-wave alarm level. This RI is a real-time value and the maximum value fits the instrumental intensity of JMA. Because FREQL, the new generation of Compact UrEDAS, improves the reliability of P-wave distinction, FREQL can issue the alarm immediately after the P-wave alarm threshold is exceeded. If FREQL had been installed instead of Compact UrEDAS, both Kawaguchi and Nagaoka observatory would issued the P-wave alarm 0.2 and 0.6 seconds after P-wave detection, respectively. Table 1 summarizes the simulation results. In this case, the P-wave alarm reached the derailed section before P-wave arrival. Accordingly, FREQL minimizes the process time for alarm.

Table 1 Summarize the simulation results

Alarm and Accident Site	Kawaguchi	Tunnel Exit	Nagaoka
5HzPGA (Gal)	846		434
RImax (MMI)	6.6 (10.9)		5.8 (9.6)
Origin Time	17:56:00.3	17:56:00.3	17:56:00.3
Recorded Detecting Time	3 s		4 s
P-wave arrival Time	2.9	3.3	3.5
Time of RI >2	3.1		4.1
P-wave Alarm Time	3.9	3.9	4.5
Time of Max. Acc >10Gal	3.4		4.7
Time of Max. Acc >40Gal	4.2		5.9
Time of 5HzPGA	7.7		9.4
Time of RImax	8.1		9.5

Fig.13 shows the details of the derailment. The derailed train, Toki #325, consisted of 10 cars, from car #10 to car #1 along the traveling direction. The number of derailed axles is 22 out of a total of 40 axles. The last car, #1, fell down the drain besides the track and tilted by about 30 degrees. The open circle indicates the location of broken window glass. The quantity of broken grass appears greater on the left due to the something bounce from the sound barrier, and tends to break one or two cars after the derailed car. The amount of broken glass from car #1 is exceeded by that of car #2.

If it is assumed that the glass broken of car #2 was caused by the derailment of cars #4 and #3, the paucity of broken glasses from car #1 suggests that car #2 did not derail during the earthquake motion. It is estimated that the frictional heat between the vehicle and the rails caused elongation and slightly rift up at the joints of 206km700m, and car #1 derailed, making car #2 derail.

Deformation performance of viaducts is specified within one cm under the loading of the seismic design force. Although the designed natural frequency corresponding to the deformation performance is 2.5 Hz, in practice it is 3.5 Hz. The viaduct may thus be considered to behave statically against the earthquake motion less than around 1.5 Hz. Fig.14 shows the relative deformation derived from the dimension of the viaduct columns. The meshed line shows the averaged deformation for each viaduct block, and it is estimated that the relative large occurred at the area

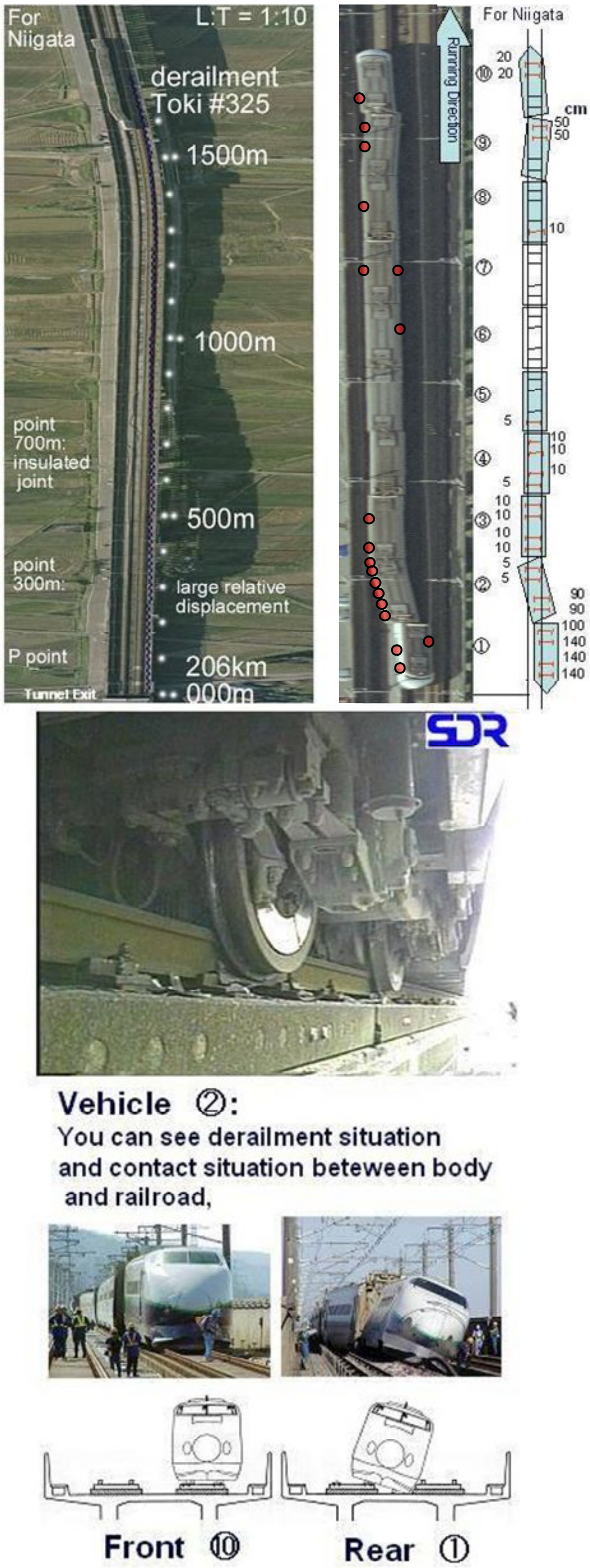


Fig.13 Detail of the derailment

farther from the tunnel exit. Taking into account the timing of earthquake occurrence, this is the point of derailment.

Fig.15 outlines the circumstances of the derailment. It seems that the derailed cars were on the large displacement section accidentally. The later the alarm reached, the more the number of derailed car, because of the risk of running the

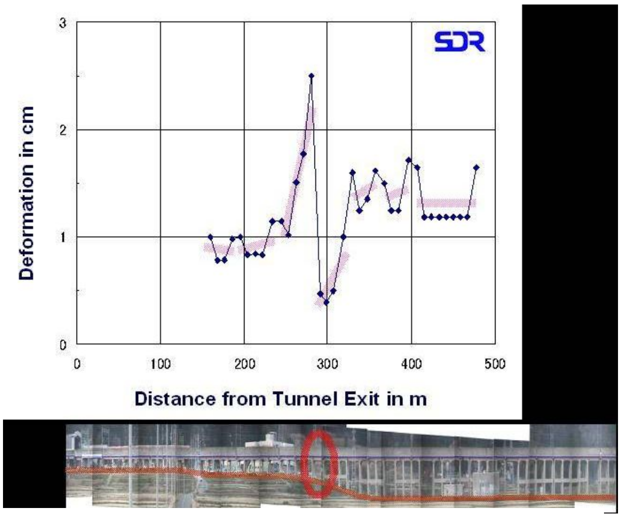


Fig.14 Performance of the deformation

large displacement section. As a result, if the friction heat release value were higher, the derailment situations were more severe. On the other hand, the early warning slows the train down, which means that the main shock hits the train before the large displacement section and decreases while the train travels the section. The number of the

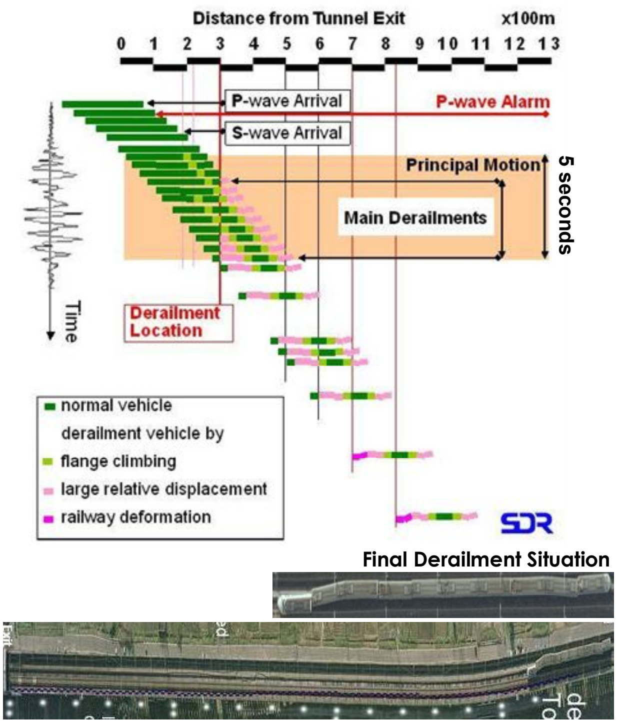


Fig.15 Estimated situation of the derailment

derailed cars is thus expected to decrease and the derailment damage must be minor. In this regard, the P-wave alarm of the Compact UrEDAS demonstrates its effectiveness at making the derailment non-catastrophic.

4. An Example of Integrated Systems for EEW and Quick Response against Strong Motion

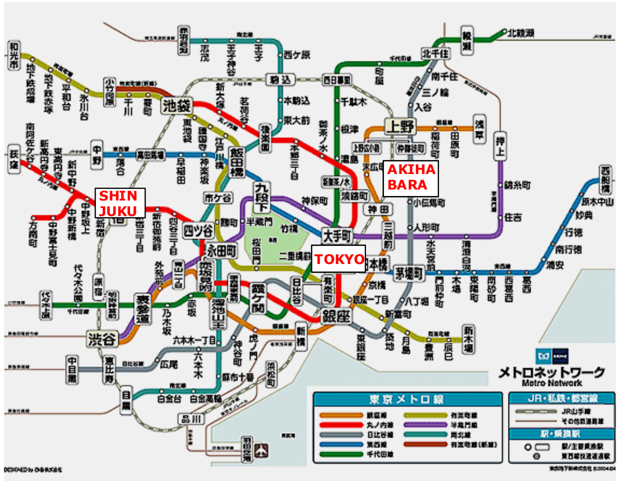


Fig.16 Subway network of Tokyo Metro Company

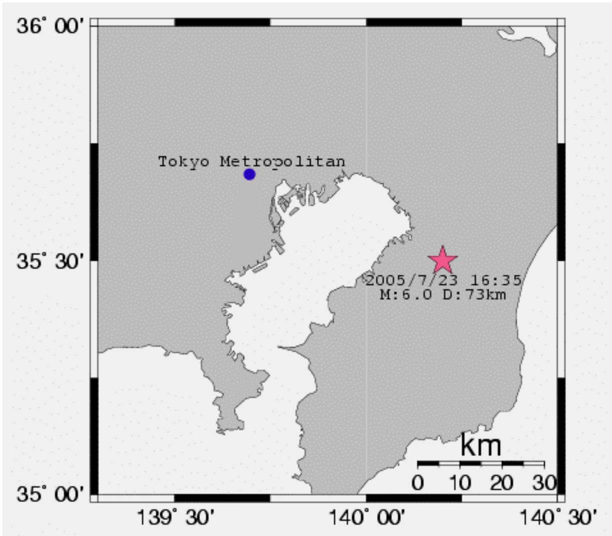


Fig.17 The 2005 Chiba North-West Earthquake

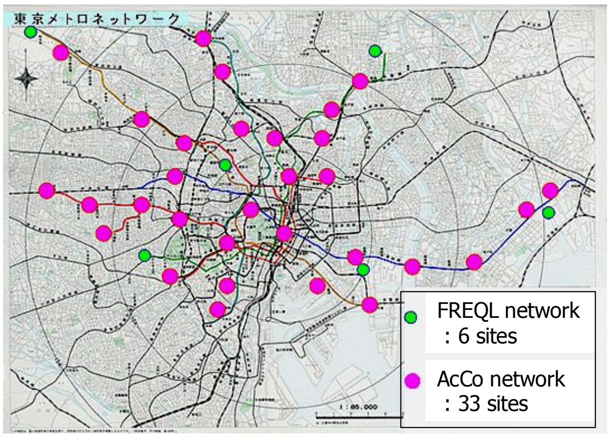
Tokyo Metro, Subway Company, built the new earthquake early warning/quick response system based on the experience of the 2005 Chiba north-west earthquake, Mjma 6.0. Tokyo Metro network is the core of the railway transportation system for the entire Tokyo metropolitan area as in Fig.16.

In July 2005, the earthquake attacked the Tokyo metropolitan area as in Fig.17. This earthquake occurred at 35.5N and 140.2E with about 73km in depth, and the maximum JMA intensity was 5+ corresponding to MMI VIII approximately. This earthquake occurred at north-west of Chiba prefecture and caused a traffic disturbance widely in Tokyo metropolitan area. All the train operation had been stopped for a long time after the earthquake, although a severe damage was not caused even in the area of high intensity. The longest down time for the train operation was more than seven hours. That of Tokyo Metro was four hours.

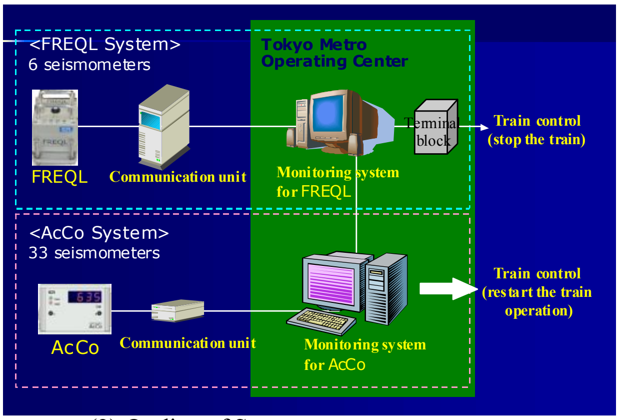
Tokyo Metro had to check all track on foot, because the control reference value for train operation exceeded.

The value of Tokyo Metro is 100Gal of 5HzPGA. This value varies by Train Company. To check the track on foot is the reason why had all train operation been stopped for a long time.

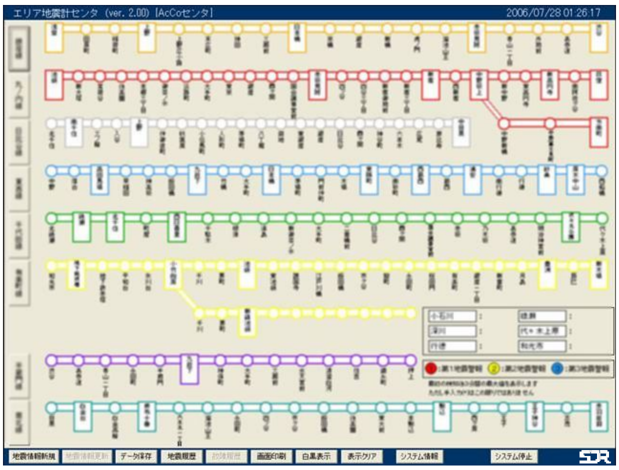
After the earthquake, we proposed a new system for early warning and quick response with basic idea as follows. It is necessary for the control against the earthquake to equip the system not only to issue the early warning but also to support the quick and rational recovery work after the earthquake. Tokyo Metro Company accepted our proposal, and replaced and built the new early warning/quick response system as followed.



(1) Networks of FREQL and AcCo



(2) Outline of Systems



(3) Monitoring System for AcCo

Fig.18 New Earthquake Early Warning System

The system consists of two seismometer networks as shown in Fig.18. One is the early warning system network consisting six sets of FREQL to control or stop the train operation immediately after the earthquake occurrence. And the other is the network of the portable digital seismometer consisting of 33 sets of AcCo in every about three kilometers mesh to grasp more detailed seismic motion on their service area.

The information from both FREQL network and AcCo network are gathered to the operation center and displayed on the individual monitoring system. The monitoring system for AcCo can indicate the integrated information from AcCo and FREQL on the subway network image. The AcCo monitoring system is also installed on the control table for each subway line.

At the time of the earthquake, the early warning system detects at first the earthquake immediately and then the 33 local seismometers inform the actual earthquake motion of each site independently and rapidly as in Fig.19. This system realized quick response and restart of the train operation because the early warning became faster and checking zone after earthquake was optimized. This updated system is expected to realize quicker response during and after.

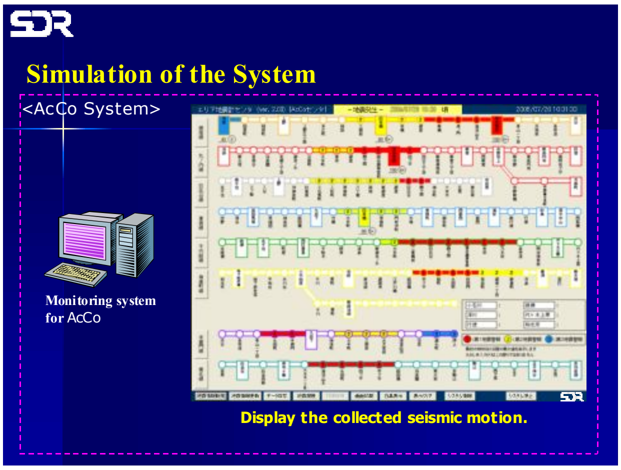


Fig.19 Display example when earthquake occurred

For the large system as the train operation, it is necessary for the control against the earthquake to equip the system not only to issue the early warning but also to support the quick and rational recovery work after the earthquake.

5. Discussion

It seems that the difference between real time seismology (RTS) and real time earthquake engineering (RTEE) is the way of contribution indirectly or directly for practical use, as same as the difference between science and engineering. RTS makes the countermeasure soon after the earthquake rational and prompt by sending information universally to be useful for public. And RTEE sends the information for certain customers as a trigger of the countermeasures against the earthquake disaster. From the view of time domain, RTS is required by the rational action after the earthquake terminated and RTEE is necessary for the immediate response just after the earthquake occurrence or earthquake motion arrival.

RTS needs high accuracy on the information but not immediate, so it is possible to utilize effectively the knowledge and experience on seismology and infrastructures as observation networks. The task are to be more accurate the information on the earthquake observation and to deliver rapidly to all people.

On the other hand, the most important aim of RTEE is to decrease the degree of the disaster or the possibility of the disaster occurrence so it is necessary to issue alarm rapidly and certainly. For this purpose, at first it must be concerned to install own observation system for the alarm, without relying the information from the other authorities. And then, it is possible to use the other information if it can be received. It is necessary to customize the way of issuing and utilizing the alarm depends on the situation for each customer and fields. Again, it is risky to rely to the information only from the other authorities using the data transmission network under the situation of earthquake.

In Japan, JMA has started delivering the EEI, Earthquake Early Information, on 1st October 2007. It is clear that EEI is belonging to RTS. So it is only a result of earthquake observation and must be delivered widely for public with no restriction for receiving. Since for some case, it may be possible to use it as alarm, but generally to say, EEI is mainly for the rational countermeasures after earthquake termination. It must be used for release of the EEW by the people quickly if the alarm is not needed. From the view of this, the most important is accuracy and the delay of few seconds is not a problem, because the error of this kind of information may cause a serious confusion. It is enough that the accurate information is delivered within one or two minutes after the event. Alarm must be released rationally and EEI may play an important role as one of the useful tools for this.

It is necessary to grasp the distribution of earthquake motion at the early stage. It is recommended to progress the earthquake disaster prevention with the combination of the public information such as EEI by JMA rather late and local dense and quick information by the people.

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