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Development of an Earthquake Early Warning System and Its Benefits

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1 Introduction

The ground motion of an earthquake resembles thunder in a sense. A person who witnesses bright lightning in the night sky prepares himself or herself for the thunder that is anticipated to follow. This time lag results from the velocity difference between light and sound. In the case of an earthquake, the velocity difference between the primary wave (P-wave) and the secondary wave (S-wave; generally, the S-wave has a larger amplitude than the P-wave, and, in the case of a nearby earthquake, the peak ground motion (principal motion) often arrives immediately after the S-wave) generates a time allowance which enables a person to start preparing for the principal motion as soon as he or she detects the preceding P-wave. Moreover, by installing seismographs near the source and analyzing the P-wave data detected by the seismographs, it will be possible to give warnings to distant locations before the P-wave arrives at those locations.

If an advance warning of ground motion can be given effectively, the number of casualties from collapse of buildings and other earthquake damages could possibly be reduced. Even when the ground motion is not so strong, such warning could contribute to reducing economic losses through automatic shutdown of machines. Furthermore, system development related to such warnings may create new business opportunities. The idea of a system for advance warning of ground motion, which was considered to be promising in various aspects as explained above, already existed from long ago. However, in order to actually build such a system, an appropriate observation network, analysis system, and communication system would essentially be required. A total renewal of Japan's seismic observational and research infrastructure triggered by the 1995 Great Hanshin-Awaji Earthquake Disaster laid the basis for putting such idea into practice.

In October 2007, the Japan Meteorological Agency (JMA) embarked on practical implementation of such idea, that is, actual operation of the Earthquake Early Warning (EEW) system[1] based on the results of its research and development efforts. During the two and half years from then until March 2010, a total of 14 EEWs were issued via television, etc. and EEWs became widely recognized and have taken root among people (these EEWs are categorized as Alerts which are explained later in this article). During this period, although there were some malfunctions caused by erroneous transmissions and seismic intensity prediction errors, the performance of the EEW system more or less fell within the anticipated scope, and EEWs were favorably reported by mass media as a case example in which results of seismic studies have been directly put to beneficial use in peoples' lives. However, since the time allowance generated by an EEW is just about sufficient from a workable standpoint, how EEWs' realistic effects can be optimized remains as a future challenge.

Practical implementation of EEWs also drew attention in terms of its technology development aspect, and the details of the technology development were introduced in *Science & Technology Trends* on three occasions.[2–4] As for the mechanism of the EEW system[5] and its usage guidelines,[6] see the detailed explanations available on the JMA website.[7] This article gives an outline of the mechanism of the EEW system, its development history, and actual state of its operation, as well as focuses on the *regressiveness* whereby the time allowance becomes shorter as the seismic intensity becomes larger, as a practical problem, and develops an argument with an eye on the limits of EEWs, while also providing the author's views.

2 Contents and Positioning of EEWs

2-1 Mechanism of the EEW System

The principle of the EEW is, as Figure 1 shows, to presume the source information (location and magnitude) using the P-wave that has arrived at the observation point nearest to the source in the nationwide seismic observation network, calculate the ground motion that is expected to occur at various locations based on this presumption, and transmit the result before the arrival of the principal motion. Because the principal motion generally arrives immediately after the S-wave, the system aims to transmit an EEW before the arrival of the S-wave. The JMA has developed a method to presume the source location and the magnitude based on information obtained at only the single nearest observation point, and sends the result derived from information at such single observation point as a first report. However, since the first report contains substantial uncertainties, the JMA sends a second report and a third report by also using the seismic waves that have arrived at the second and subsequent nearest observation points.

Although the principle is thus simple and clear, the actual situation is quite complicated, as indicated in the following specific example. There are a total of about 1,000 observation points nationwide, combining about 200 multifunctional seismographs of the JMA and about 800 high-sensitivity seismographs (Hi-net) of the National Research Institute for Earth Science and Disaster Prevention (NIED). The average distance between these points is about 20 km. Therefore, in the case of an inland earthquake, the average horizontal distance to the nearest observation point will be about 10 km, which will be used as the representative value. When the depth of the source is assumed to be 10 km, the source distance to the nearest observation point will be about 14km. Figure 2 shows a time chart where an EEW is received at a location farther away from the source than the observation point, with a source distance of 30 km. While the seismic wave velocity differs by depth, the P-wave velocity at the depth of 10 km was assumed to be 6km/sec. and the S-wave velocity at the same depth to be 3.5 km/sec. Further, the delay expected when passing through a shallow layer[8] was also taken into consideration in the estimation. The P-wave arrives at the nearest observation point 3.0 seconds after the earthquake occurrence. Under the present conditions, it takes about 5.5 seconds on average to transmit the first report, so the first report reaches the target location 8.5 seconds after the earthquake occurrence. Since the S-wave arrives at the target location 10.7 seconds after the earthquake occurrence, the EEW will be just about in time for the principal motion in this case. However, given that a transmission delay will occur in real circumstances, we need to consider that in the case shown in Figure 2, that is, at a location within a 30 km radius from the source, the EEW will not practically reach the recipients in time. The *earthquake disaster belt*,[NOTE] which appeared at the time of the Great Hanshin-Awaji Earthquake Disaster (M7.3), roughly coincides with this 30 km-radius zone. Therefore, even if the EEW system did exist at the time, the EEW unfortunately would not have reached the recipients in time. Because of this, the JMA indicates the following notice: “In areas that are close to the focus of the earthquake, the warning may not be transmitted before strong shakes hit." Of course, if the distance becomes longer, the time allowance will also become longer. In this estimation as well, the time allowance increases by about 3 seconds for every 10 km distance away from the source. In the case shown in Figure 2, the P-wave arrives at the target location 5.7 seconds after the earthquake occurrence, so the preceding P-wave shaking will have already started at the target location before the arrival of the EEW. Accordingly, if the later-mentioned ground-motion-detecting control system operates with the arrival of the P-wave, about 5 seconds of time allowance can be secured before the arrival of the S-wave.

2-2 Positioning of EEWs

At present, four types of earthquake-related information are issued by Japanese public organizations (Table 1): (i) Strong Ground Motion Prediction; (ii) Earthquake Prediction (currently only

[NOTE]
The *earthquake disaster belt* refers to a belt of land along Kobe's urban area that suffered concentrated damage in the Hanshin-Awaji Earthquake Disaster. Ground motion is considered to have been amplified due to its unique subsurface structure composed of a fault and a sedimentary basin.

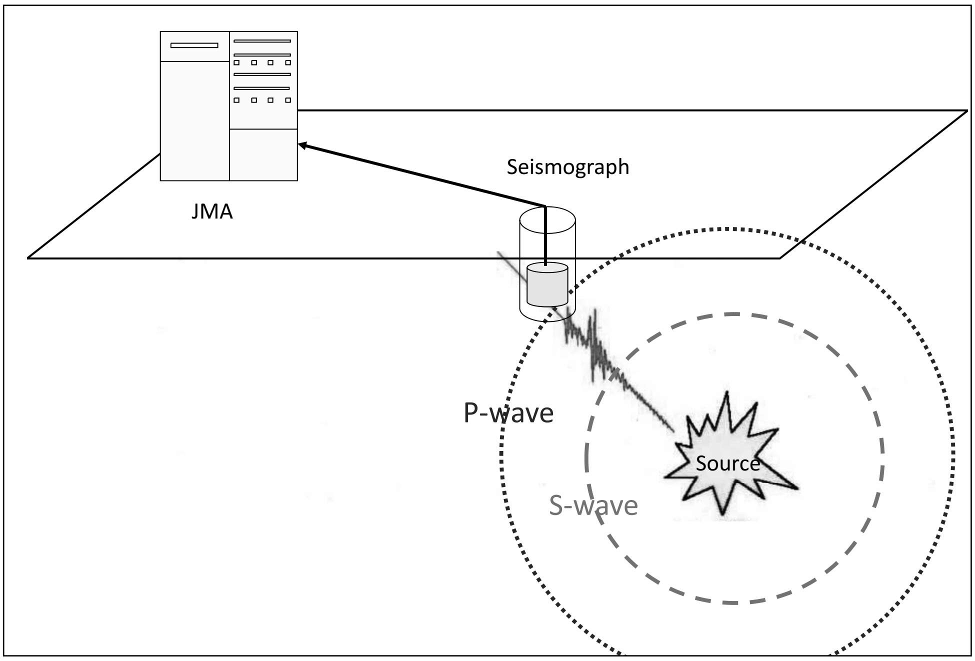

Figure 1 : Principle of the Earthquake Early Warning

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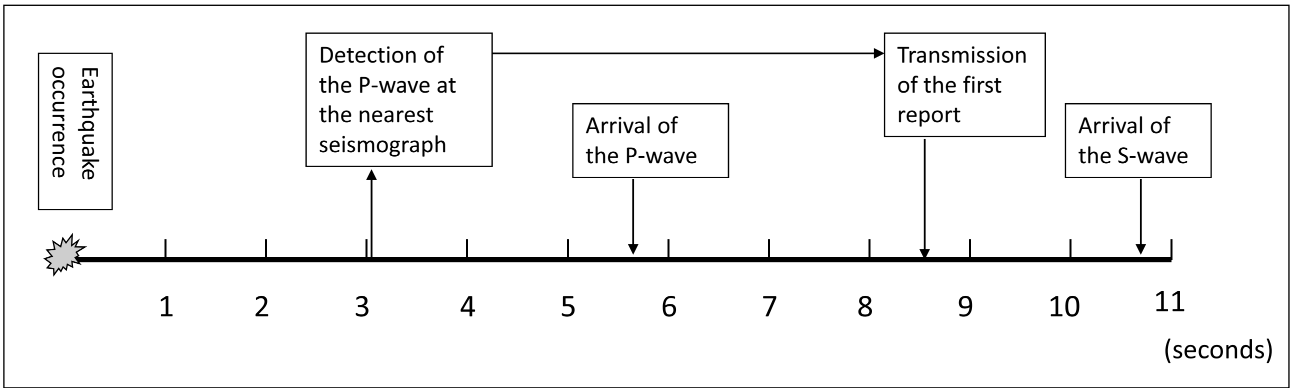

Figure 2 : Time Chart of the Seismic Wave and Transmission of an Earthquake Early Warning (Source Distance =30 km)

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targeting Tokai Earthquake); (iii) Earthquake Early Warning; and (iv) Earthquake Information. These are listed in the order of time sequence in relation to the earthquake occurrence. The information listed in (i) and (ii) is issued before the earthquake occurrence, and the information listed in (iii) and (iv) are issued after the earthquake occurrence. The EEW indicated in (iii) can be positioned as a safeguard based on the assumption that general earthquake prediction is not possible at present, while at the same time, it can be regarded as information issued prior to (iv) Earthquake Information aimed at identifying the status of disaster caused by an earthquake occurrence.

2-3 Categories of EEWs

As Table 1 shows, the EEWs are categorized into an Advance Notice of Ground Motion (hereinafter referred to as an "Advance Notice") and a Ground Motion Alert (hereinafter referred to as an "Alert"). While these categories are strictly defined, a simple criterion for their issuance is whether or not ground motion with a seismic intensity of 5 lower or greater is predicted. If the predicted ground motion is less than seismic intensity 5 lower, only an Advance Notice is issued, and if it is 5 lower or greater, an Advance Notice as well as an Alert are issued. An Advance Notice is issued via the Japan Meteorological Business Support Center to expert users who have dedicated terminals. An Alert is issued via television, radio, mobile phones, and anti-disaster radio communication systems to residents of areas where ground motion with a seismic intensity of 4 or greater is predicted. The former entered into operation in August 2006 and the latter in October 2007.

Table 1 : Principle of the Earthquake Early Warning

No.	Item	Time Span	Category	Contents	Issuer	Media
1	Strong Ground Motion Prediction	30 to 50 years earlier	30 year probability	Probability of occurrence of an earthquake of seismic intensity 5 lower, 5 upper, 6 lower, or 6 upper during the relevant period	Headquarters for Earthquake Research Promotion of the Ministry of Education, Culture, Sports, Science and Technology	Booklets, newspapers, and the NIED website
			50 year probability			
2	Earthquake Prediction	A few hours to a few days earlier	Tokai Earthquake Report	Occurrence of a phenomenon that cannot be immediately determined to be a precursor/occurrence of a notable earthquake within the assumed source area though not related to a Tokai Earthquake	JMA	Television, radio, newspapers, and the JMA website
			Tokai Earthquake Advisory	Occurrence of a phenomenon that is likely to be a precursor		
			Tokai Earthquake Warning	Announcement that a Tokai Earthquake is expected to occur		
			Warning Statement	Statement warning of occurrence of a Tokai Earthquake	Prime Minister	
3	Earthquake Early Warning	A few seconds to a few tens of seconds earlier	Advance Notice of Ground Motion	Transmitted when ground motion with a maximum seismic intensity of 3 or greater or a magnitude of 3.5 or greater is predicted	JMA (licensed business operators)	Dedicated terminals, etc.
			Ground Motion Alert	Transmitted when ground motion with a maximum seismic intensity of 5 lower or greater is predicted, to areas with a predicted seismic intensity of 4 or greater	JMA	Television, radio, mobile phones, etc.
4	Earthquake Information	A few seconds to a few minutes later	Seismic Intensity Information	Regional information on the ground motion that occurred	JMA	Television, radio, newspapers, and the JMA website
			Source Information	Information on the source and magnitude of the earthquake that occurred		

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3 Background and History of Development of the EEW System

3-1 Ground-Motion-Detecting Control

An idea of detecting ground motion immediately after an earthquake occurrence and controlling automatic shutdown of systems and the like had already been adopted by a number of systems before the development of the EEW. For example, in the case of a microcomputer meter that is commonly found in Japanese homes, a ground motion detector is installed within a gas meter, and when the sensor detects ground motion exceeding a specific level, the gas supply is instantly shut off automatically. Since Tokyo Gas Co., Ltd. introduced the system in the 1980s, it has come to be provided as standard equipment by gas suppliers nationwide including suppliers of propane gas.

Nuclear power plants employ a system to automatically shut down nuclear power reactors when a seismograph buried in the ground under the reactor core detects strong ground motion (about 200 gal). Recently, the Onagawa Nuclear Power Station went into an emergency shutdown from the 2003 Sanriku-Minami Earthquake (M7.1), the Kashiwazaki-Kariwa Nuclear Power Station from the 2007 Chuetsu-Oki Earthquake (M6.8), and the Hamaoka Nuclear Power Station from the 2009 earthquake in Suruga Bay (M6.5). In all of these cases, the automatic shutdown system functioned as expected. However, we need to be aware of the fact that the control rods for the shutdown were inserted amidst strong shaking.

Elevators, which are often used in our daily lives, also employ a function to automatically stop at the nearest floor when detecting ground motion. In reality, however, there are constant accidents where elevators stop upon an earthquake without the door opening, and people are trapped inside the elevators for many hours.

While these are three major examples, other original control systems are likely to be employed in various other scenes as well. If the level of the ground motion to be detected is set low, it will be possible for the control system to be effected by the arrival of the P-wave and to shut down the system before the arrival of the principal motion. Such system resembles the function of the EEW, but the EEW is superior in that it has the potential to initiate the response measure even before the arrival of the P-wave.

3-2 Prior case example: Development and performance of UrEDAS

The Urgent Earthquake Detection and Alarm System (UrEDAS) is a system for having trains come to an emergency stop at the time of an earthquake based on information sent from seismic observation points established along Japan Railways Shinkansen (bullet train) lines. It is the world's first system that materialized the concept of the EEW. UrEDAS, developed in the 1980s, experienced the first challenge at the time of the Chuetsu Earthquake on October 23, 2004 (M6.8). According to a developer, Yutaka Nakamura,[9,10] Joetsu Shinkansen Toki No. 325, which was traveling at a place 10-odd km in horizontal distance from the epicenter, received an emergency stop signal 2.5 seconds prior to the arrival of the principal motion, and stopped after traveling 1600 m from that point. As a result, although the train was derailed, it caused no casualties. The train is estimated to have slowed down by about 8 km per hour from the initial speed of 195 km per hour, during the 2.5 seconds. It is only a slight slowdown, but its effect cannot be ignored when a train is traveling at a high speed. It can be considered as the world's first example of a case where the concept of the EEW proved effective in a real situation.

3-3 Process toward development of the EEW

The Headquarters for Earthquake Research Promotion (HERP) of the Ministry of Education, Culture, Sports, Science and Technology, the establishment of which was prompted by the Hanshin-Awaji Earthquake Disaster, formulated "The Promotion of Earthquake Research: Basic comprehensive policy for the promotion of earthquake observation, measurement, surveys and research" (April 23, 1999)[11] as guidelines on research and development concerning earthquake countermeasures. One of the four basic measures indicated in this policy was *promotion of real-time transmission of earthquake information*, and development of the EEW was promoted under this measure. However, the concept of *real-time earthquake information* in this measure had placed more focus on ascertainment of the situation upon disaster occurrence, rather than the EEW. At the time, Hiroo Kanamori at the California Institute of Technology had advocated the keyword "real-time seismology." This was a study aimed at quickly analyzing the actual conditions of an earthquake that has already occurred, and ascertaining the extent and spread of damage on a real-time basis, thereby using such information for implementing disaster countermeasures that meet real needs. "Real-time" was adopted as a keyword in the measure above due to a serious regret that there was a delay in ascertaining the actual situation at the time of the Hanshin-Awaji Earthquake Disaster. In that sense, development of the EEW is likely to have been positioned as a task of secondary importance at the time of formulation of the measure. However, with the development of the digital strong-motion seismograph network (KiK-net) throughout Japan, the overall focus of "real-time research and development" gradually shifted toward practical implementation of the EEW.

Alongside such developments, the JMA was promoting development of Nowcast Earthquake Information based on a network of multifunctional seismographs at 200 locations nationwide, in response to Meteorological Council Report No. 21 (May 2000). Also, NIED was conducting development of Real-time Earthquake Information based on the Hi-net observation network of seismographs at 800 locations. Both of these projects had the same purpose as the EEW, which was to send information on earthquake occurrence at the earliest possible timing, and they were being promoted separately. Later, when development of the two projects reached a certain point, those projects were combined into a new project entitled "Research Project for the Practical Use of Real-time Earthquake Information Networks" (FY2003–2007),[12] which later gave birth to the Earthquake Early Warning. This project not only engaged in the development of EEW methodologies, but also in the new research field of how the EEW can be effectively used.

3-4 Developments overseas

Research, development, and operation of a system for issuing alerts immediately before ground motion, similar to the EEW, are also carried out in other countries, including the United States, Mexico, Taiwan, Rumania, and Turkey. In the United States,[13] Hiroo Kanamori et al., who have advocated real-time seismology, have indicated the potential of a system for issuing alerts immediately before ground motion, and have been calling for dissemination of such system, but such system has yet to enter into operation.

As discussed later, a system similar to the EEW is more effective against subduction-zone earthquakes than against inland earthquakes, so such system is drawing particular attention in Mexico and Taiwan that are located on subduction zones similar to Japan. In Mexico,[14] based on the lesson learned from the 1985 Michoacán earthquake (M8.0), Centro de Instrumentación y Registro Sísmico (CIRES; Center for Seismic Instrumentation and Recording)[15] launched operation of a system for issuing an alert immediately before ground motion called "Sistema de Alerta Sísmica de la ciudad de México (SAS)." This system has played the role of immediately issuing a notice of occurrence of a subduction-zone earthquake along the Pacific Ocean, to Mexico City, which is about 300 km away. During the four years of operation from August 1991, a total of 292 alerts were issued. At the time of an earthquake of M7.3 that occurred in September 1995, the notice was issued 72 seconds before the arrival of the principal motion. In Taiwan as well,[16] a system with a similar purpose called "Virtual Subnetwork" (VSN) is under operation, and alerts are issued to cities about 150 km away, with a time allowance of 20 seconds or more. This system has issued alerts for 54 earthquakes during a year-and-a-half period from December 2000.

In Romania,[17] an M8 earthquake is expected to occur at a depth of 150 km in the suburbs of Bucharest. To prepare for this earthquake, a proposal has been made to construct an Early Warning System (EWS) which can be expected to create a time allowance of 25 seconds. In Turkey,[18] an Istanbul Earthquake Rapid Response and Early Warning System (IERREWS) is proposed for creating a time allowance of 8 seconds, assuming earthquakes that occur on the Marmara Fault in the Istanbul suburbs.

In this way, systems for the same purpose are being developed or operated in various other countries, and their performance and effects vary depending on the regionality or the national characteristics. Among these, Japan's EEW system is considered to stand out in that it is based on precise analysis of information obtained from an exhaustive nationwide observation network.

4 Actual Status of Operation of the EEW

4-1 Advance Notices and Alerts

As mentioned above, EEWs issued in Japan are distinguished between Advance Notices and Alerts. While the distinction is based on the level of the target seismic intensity, the target recipients also differ as a result of the difference in their transmission methods. This difference also brings about difference in the basic characteristics between Advance Notices and Alerts. Simply put, the former are intended for expert users and the latter are for general users. Figure 3 shows their respective transmission methods.

An Alert is issued residents of target areas via television, radio, mobile phones, etc. when ground motion with a seismic intensity of 5 lower or greater is predicted. During a period of two and a half years until April 2010, a total of 14 Alerts were actually issued, including three Alerts for ground motion with a predicted seismic intensity of 6 lower or greater (the Iwate-Miyagi Nairiku Earthquake in June 2008; the Northern Iwate Intraslab Earthquake in July 2008; and the earthquake in Suruga Bay in August 2009). Meanwhile, there were five instances where an Alert was not issued although ground motion of seismic intensity 5 lower was observed. The reason was that, in all of these instances, the maximum seismic intensity was predicted to be 4. In an Alert, information on the seismic intensity distribution and the time allowance is omitted, and only the place name of the epicenter and the names of areas where strong ground motion is predicted to occur are reported.

An Advance Notice, on the other hand, is issued to business operators and individuals that have contracted with the Japan Meteorological Business Support Center, via dedicated terminals. The number of Advance Notices issued during the two and a half years until April 2010 totaled 1,391, which is quite a large number. This is because Advance Notices also cover predicted ground motion of M3.5 or greater, in other words, relatively small earthquakes. Among these, ground motion of seismic intensity 4 or greater was observed in 90 instances. Since an Advance

Notice includes information on the source, it is possible to customize the contents of the notice into more detailed information on seismic intensity by using such information. At present, however, a license from the Director-General of the JMA is required in order to provide such additional information. The number of licensed business operators as shown in Figure 3 is over 50 as of 2010.

4-2 Patterns of use of Advance Notices

Figure 3 shows various fields of use as sectors to which Advance Notices are sent. In these sectors, users are assumed to use earthquake information as professionals in the respective fields.

The Research Project for the Practical Use of Real-time Earthquake Information Networks introduced in Section 3-3 positioned effective use of Advance Notices as one of its research tasks. In order to pursue this research task, an incorporated nonprofit organization, the Real-time Earthquake Information Consortium (REIC), was established. REIC has focused on 14 fields, including the following: fire and disaster prevention; disaster prevention sites; medical care; in-home automatic control; power-generating stations and factories; communications; schools; dams; FM character multiplex tuners; LPG automatic shutoff; and building facilities. For these fields, REIC has promoted development of specific methods for effectively using Advance Notices, in cooperation with technical experts engaged in disaster prevention projects in the respective fields.[19, 20]

Uses of Advance Notices can roughly be divided into two major types. One is automatic control using the signals from dedicated terminals. For example, elevators are equipped with a ground-motion-detecting control system, but still, there have been a constant number of incidents where people are trapped in elevators as a result of ground shaking from an earthquake. An expectation that use of Advance Notices, which have the potential of controlling elevator operation before shaking, will contribute to reducing the number of such incidents is one of the most clear-cut effects of Advance Notices. Advance Notices are issued for ground motion of seismic intensity 3 or greater. Such level of shaking does not pose a problem in everyday life, but it has the possibility of inducing accidents at constructions sites, particularly in crane operations. Also, in precision processing factories and data centers, even slight shaking could cause misalignment or data deficiency leading to substantial economic loss. In that sense, automatic control, such as automatic shutdown, based on Advance Notices is likely to prove useful in many instances.

The other type of use is where Advance Notices cannot be used for automatic control, but can be used as meaningful information. For example, for a doctor attending surgery in a hospital, an advance notice of soon-expected shaking would be extremely valuable for allowing him/her to prepare for the shaking. Such instances are expected to potentially exist also in fields other than those shown in Figure 3. An important point is that, in both types of uses, the target recipients of Advance Notices are professionals in the respective fields. Although it is possible for individuals to receive Advance Notices, Advance Notices basically assume the recipients to be capable of taking appropriate measures. Therefore, the recipients are required to have professional awareness and sense.

4-3 Effects of Alerts

While Advance Notices target professionals, Alerts target the general public. The JMA website provides information on how to respond to an Alert according to six scenariossuch as at home or outside.[6] However, it is considered to be difficult in actuality to promptly respond to an Alert in such different ways according to the scenario. The general public cannot be treated in the same manner as professionals from whom training achievements can be expected. Many people are likely to be surprised by a sudden alert, unable to move not knowing what to do. Although such response is generally considered to be undesirable according to an instruction manual[19] and other documents, the author does not necessarily think so. As in the example of lightning mentioned in the beginning of this article, people may be unable to move, but at least at that moment they would be able to prepare themselves for what is about to come.

When ground motion of seismic intensity 5 lower or greater is predicted at any one location, an Alert is issued to all areas where ground motion of seismic intensity 4 or greater is predicted. Consequently, the level of shaking experienced by the recipients in most locations would be about seismic intensity 4. Ground motion of seismic intensity 4 hardly causes any substantial damage, but according to the author's experience, people would suffer considerable

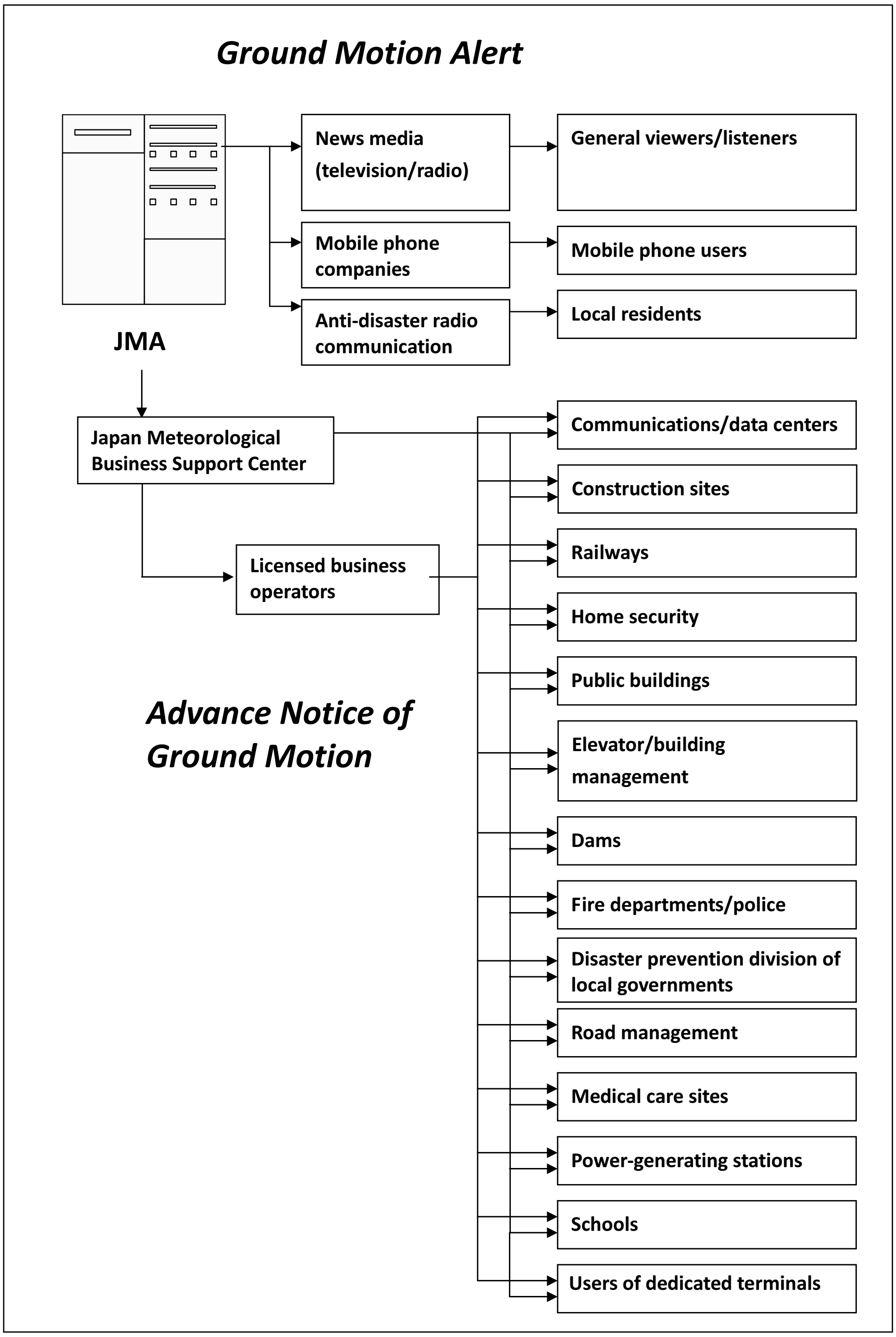

Figure 3 : Transmission Patterns of Earthquake Early Warnings

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psychological fear when such level of shaking occurs. It is because we do not know how large the sudden shaking will swell. In such an instance, if information on the maximum seismic intensity in each area is issued in advance, it is likely to have sufficiently high psychological effect against such fear. While the current Alert does not include information on the predicted seismic intensity, whether or not such information should be included would be one of the issues to be studied in the future.

The most problematic case assumable for receiving an Alert is at the time of driving a car. This is an instance where the general public is required to make a response as a professional. The JMA presents three instructions including "do not quickly brake," but since the circumstances would differ for each and every driver, it would remain a difficult problem in the future.

5 Problems of the EEW and the Direction for Improvements

5-1 Regressiveness between seismic intensity and time allowance

As mentioned in the introductory section, the EEW involves regressiveness whereby the time allowance becomes shorter as the seismic intensity becomes larger. This phenomenon is explained below using graphs. Figure 2 indicates a time chart for arrival of the first report to a location with a source distance of 30 km, but here, the seismic intensity is not taken into consideration in making the estimation. Figure 4 shows the time relation between the S-wave arrival time and transmission of the first report (the shaded portions in the lower part of the graphs) for areas where the seismic intensity will be 4, 5 lower, 5 upper, 6 lower, and 6 upper, according to the respective earthquake magnitudes. The time difference between the S-wave arrival time and transmission of the first report is the time allowance. This estimation directly applies the attenuation relation of ground motion and the source area evaluation method used by the JMA. The left graph shows the case of an inland earthquake, and the right graph shows the case of a subduction-zone earthquake. The assumed source depth is 10 km, and the horizontal distance to the nearest observation point is set at 10 km for the inland earthquake, and 50 km for the subduction-zone earthquake. The site amplification factor is assumed to be 1.0, and, based on a report by the JMA, the first report is assumed to be transmitted 5.5 seconds after the detection of the P-wave.

These graphs reveal that, where the seismic intensity is identical, the time allowance becomes longer as the magnitude becomes larger, that is, as the earthquake becomes larger. On the other hand, when the magnitude is fixed, or, when focusing on a single earthquake that has occurred, regressiveness is observed whereby the larger the seismic intensity the shorter the time allowance is.

According to the JMA document "Relation Between Instrumental Seismic Intensity and Damage, etc.,"[21] serious damage such as destruction of buildings occurs when the instrumental seismic intensity is about 5.5 or greater, that is, when the seismic intensity is 6 lower or greater. This also applies to buildings built in or before 1981, the year in which the Building Code was enacted. For example, in the left chart in Figure 4, where the magnitude is M7.2, the S-wave arrives at the outermost edge of the area with seismic intensity of 6 lower 11.6 seconds after the earthquake occurrence, and the first report is transmitted 8.5 seconds after the earthquake occurrence, generating a time allowance of about 3 seconds. Even for the same earthquake, in an area with seismic intensity of 4,

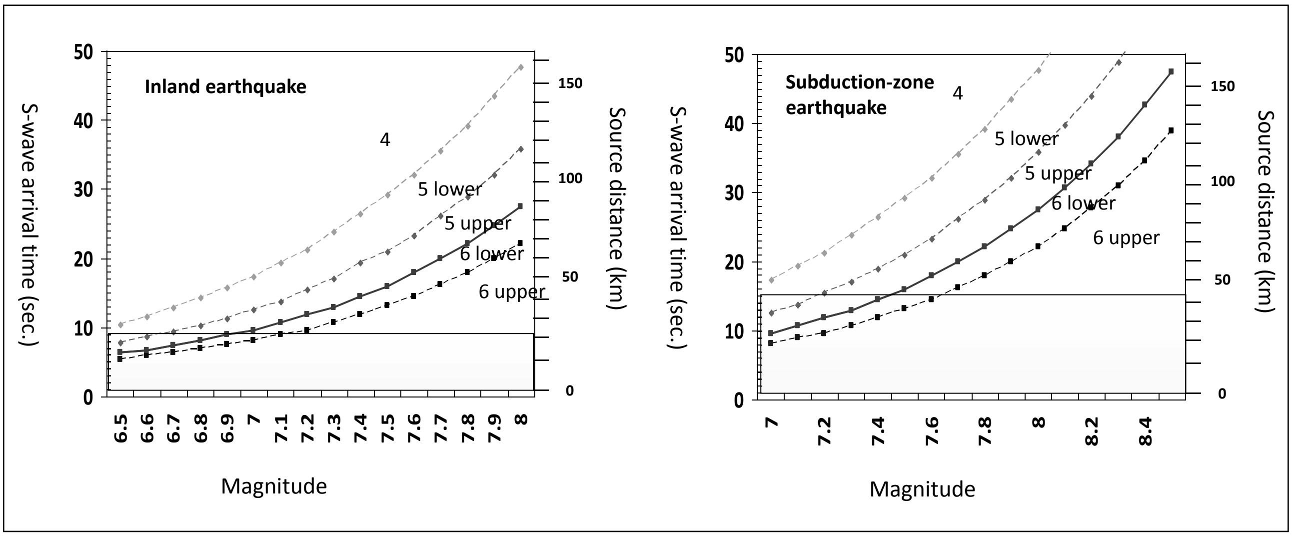

Figure 4 : S-wave Arrival Time by Seismic Intensity
Left graph: inland earthquake (source depth: 10 km; horizontal distance to the nearest observation point: 10 km; and site amplification factor: 1.0)
Right graph: subduction-zone earthquake (source depth and horizontal distance: same as above; and horizontal distance: 50 km)
Shaded portion: time elapsed until the transmission of the first report (Any portion beyond this shaded portion represents a time allowance.)

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the S-wave arrives 21.3 seconds after the earthquake occurrence, so there will be a time allowance of 12 seconds or more. Figure 5 shows the distribution of time allowance and seismic intensity for the actual case of the Iwate-Miyagi Nairiku Earthquake (M7.2) on June 14, 2008. The figure reveals that the distribution more or less coincides with the estimation in Figure 4.

Since 1900, earthquake disasters causing deaths of 10 or more persons have occurred 36 times in

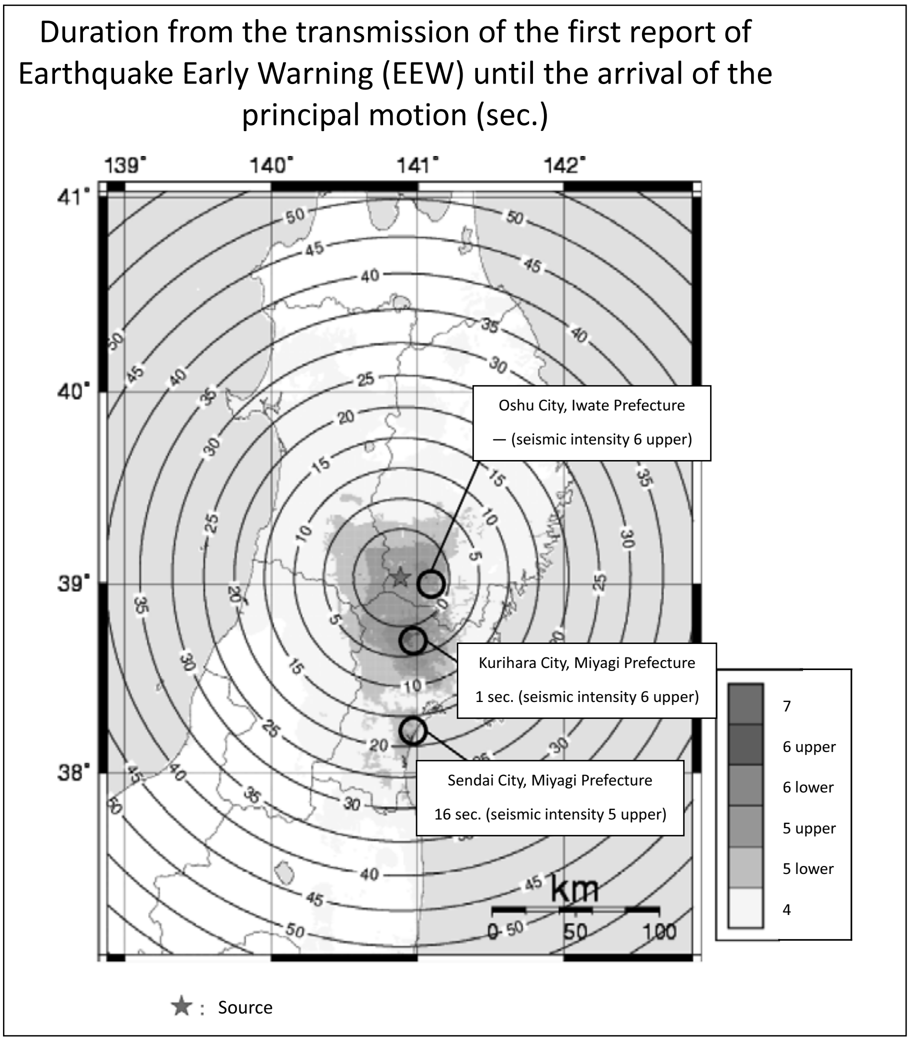

Figure 5 : Actual Example of the EEW Issued for the 2008 Iwate-Miyagi Nairiku Earthquake (M7.2)

Source: JMA[7]

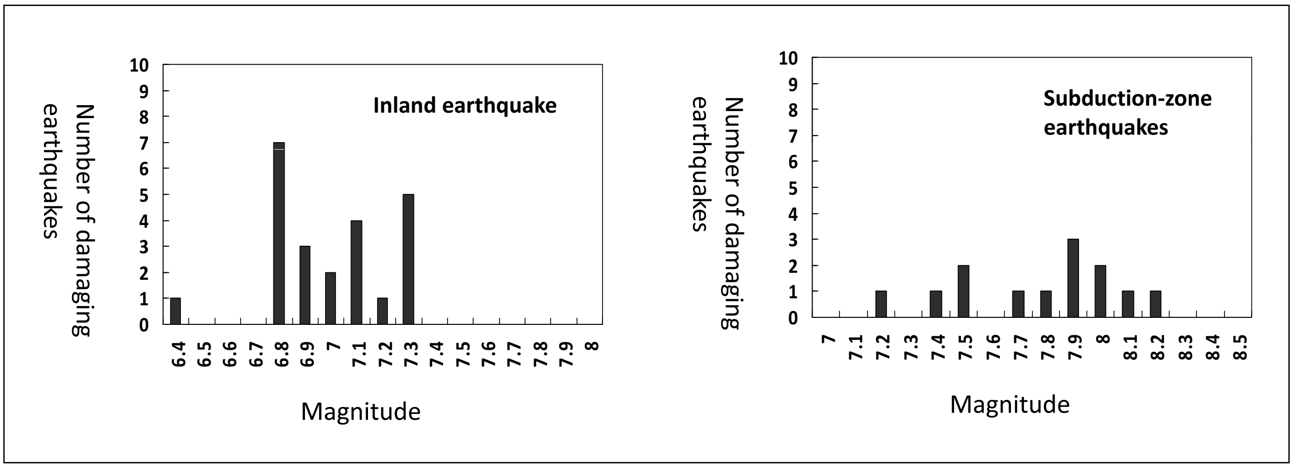

Figure 6 : Number of Damaging Earthquakes Causing Deaths of 10 Persons or More Since 1990
Left graph: Inland earthquakes
Right graph: Subduction-zone earthquakes (including earthquakes along the eastern margin of the Japan Sea)

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Japan, including the 1995 Hanshin-Awaji Earthquake Disaster (M7.3) which caused a large-scale disaster recently. Figure 6 classifies such earthquake disasters into those of inland earthquakes (left graph) and those of subduction-zone earthquakes (right graph), and indicates the respective distributions of magnitudes (earthquakes that have occurred along the eastern margin of the Japan Sea are included in subduction-zone earthquakes). The average magnitude of the 23 inland earthquakes was M7.0±0.2. According to Figure 4, when the transmission delay is taken into consideration, there would hardly be any time allowance for ground motion with a seismic intensity of 6 lower or greater caused by these earthquakes. Therefore, even if an Alert had been issued for these earthquakes, it is questionable whether it would have had an effect to reduce the number of deaths.

On the other hand, the average magnitude of the 13 subduction-zone earthquakes was M7.8±0.3, and even for ground motion with seismic intensity of 6 lower or greater, a time allowance exceeding 10 seconds would be generated depending on the place. The right graph in Figure 4 has assumed the horizontal distance from the nearest observation point to the source to be 50 km, but if a seismograph is installed on the seafloor near the source, the time allowance would be even longer. Figure 7 indicates the positions of cabled seafloor seismic observation points where observation has already been implemented. They are all located along the Pacific Ocean, such as off

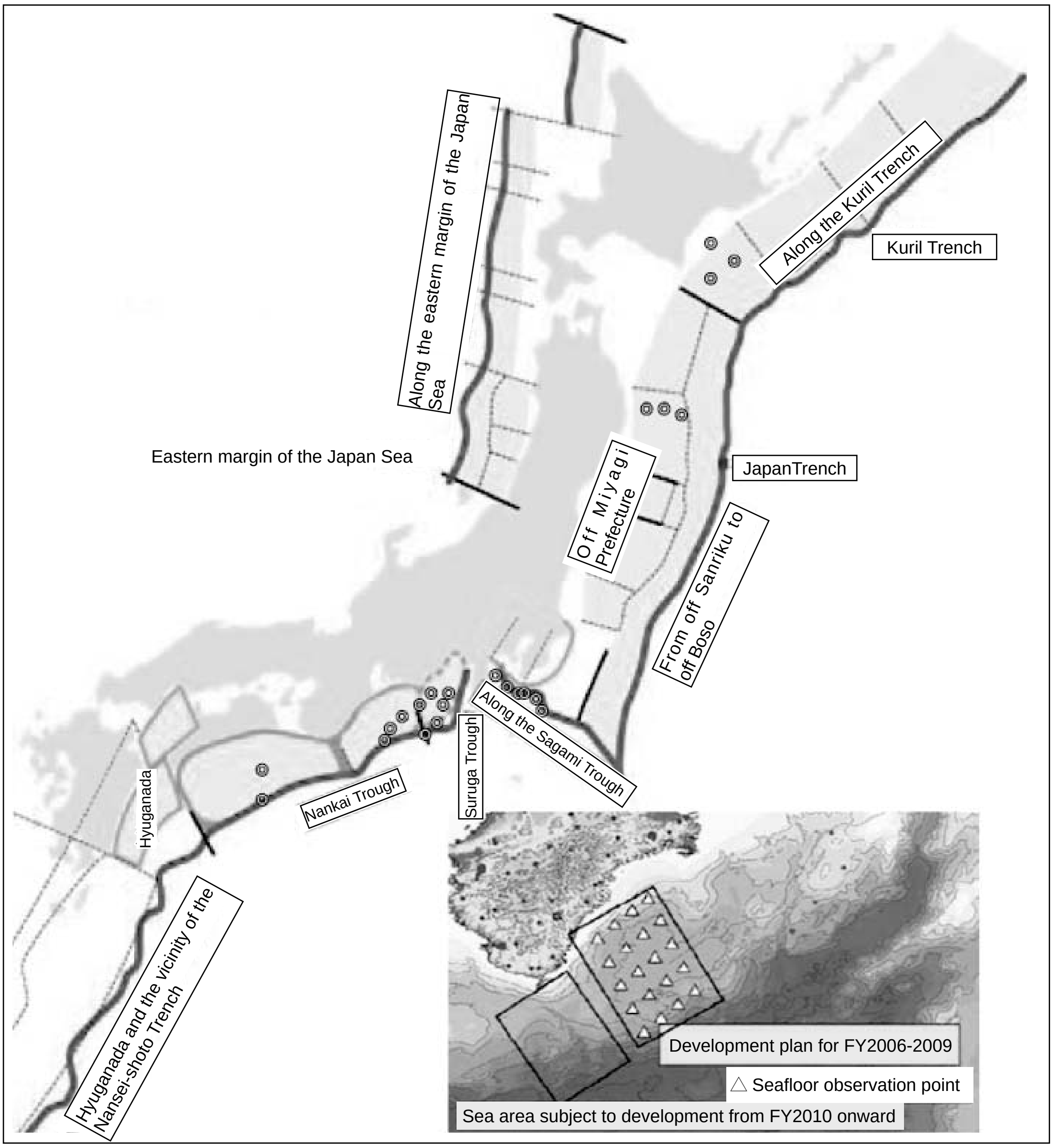

Figure 7 : Assumed Subduction-zone Earthquakes and Cabled Seafloor Seismographs (◎)
Bottom right figure: the Dense Oceanfloor Network System for Earthquakes and Tsunamis being developed by JAMSTEC in Kumanonada for Nankai Trough earthquakes

Prepared by the STFC based on documents of HERP[22] and JAMSTEC[23]

Kushiro, off Sanriku, Sagami Bay, Enshunada, and off Cape Muroto. A particularly notable location is off Kii Peninsula. This location is predicted as becoming the source of Tonankai-Nankai Earthquakes in the near future, and as shown in the bottom right figure in Figure 7, a massive-scale, seafloor seismic observation network is currently being developed there by the Japan Agency for Marine-Earth-Science and Technology (JAMSTEC).[23] Therefore, Alerts can be expected to fully demonstrate their intended function for such subduction-zone earthquakes.

5-2 Challenges of the prediction techniques and improvement efforts

Continued improvement efforts are being made for the currently operated EEW. The key point of improvement is to raise the accuracy of the predictions.

While the first report is information that has been analyzed by using only the P-wave signal received at the nearest observation point, techniques called the level method[5] and the B-Δ method[5] are currently used in order to presume the source. The level method sends out information at the point when strong motion of 100 gal or more is detected. It hardly requires any processing time, but information from multiple observation points would be necessary in order to conduct source analysis. On the other hand, the B-Δ method conducts source analysis based only on information from a single observation point. Since source analysis involves a total of five unknown values including the location, the origin time, and the magnitude, it is basically extremely difficult to determine all of these values based on information from only a single observation point. However, the B-Δ method manages to promptly provide source information while supplementing lacking information by an ingenious approach, which is to determine the direction from which the wave has arrived based on signals of three components, and to determine the location of the source by presuming the distance using the waveform characteristic that the farther the earthquake is, the higher the scattered wave component will be. Furthermore, by using techniques that also consider information such as that the seismic wave has not arrived at surrounding observation points, such as the territory method,[5] the grid search method,[5] and the arrival/non-arrival method,[24] quite accurate information on the source location can be obtained within an extremely short time even at present.

In contrast, it is difficult to infer the magnitude. Although the magnitude is generally determined by using information on the entirety of seismic waves, in the first report the magnitude needs to be inferred based only on the start portion of the P-wave. As a result, the predicted seismic intensity inevitably contains a certain extent of error or uncertainty. While the magnitude is supposed to be determined based on the maximum amplitude of all phases of seismic waves, the magnitude value in the first report of the EEW is calculated based only on the first three seconds of the waveform of the P-wave. If the slip velocity on the fault plane is assumed to be 1 m/sec., earthquakes with a maximum slip of 3 m, that is, earthquakes of up to M7.5, can be evaluated. Also, if the rupture propagates, or, if the fault plane grows at the S-wave velocity, correct evaluation can be made for earthquakes with a maximum fault length of 20 km, that is, earthquakes of up to M7.0. Due to these limitations, the magnitude cannot be correctly evaluated in the EEW for a large earthquake of the M7 class or greater. Although the estimated value of the magnitude is updated by the second report and the third report along with the growth of the seismic waves, there is an unavoidable problem that the magnitude in the first report tends to be underevaluated in the case of a large earthquake. Over the past two and a half years, the predicted seismic intensity did not reach the Alert standard in five out of the 19 cases where ground motion of seismic intensity 5 lower or greater was actually observed. This problem is regarded as a particularly important challenge to be addressed in improving the EEW. Various new techniques have been proposed, but the mutually opposing nature of instantaneousness and accuracy remains until the end.

Similarly, identification of the source area of a massive earthquake is another important challenge. The rupture of an earthquake does not remain in the vicinity of the source, but for example, in the case of an M8 earthquake, a source area exceeding 100 km will be ruptured, spreading even to a location far away from the source which could be hit by ground motion of seismic intensity 6 class. The current analysis technique makes approximate calculation using the distance from a sphere of a size corresponding to the magnitude, in place of the source distance, but the calculated distance using this method will deviate more substantially from the actual distance as the earthquake becomes larger. Accordingly, a number of techniques have been devised for instantly identifying the source area. Although constant efforts are made to raise the accuracy of the EEW, the difficulty of handling larger earthquakes and the scarcity of the opportunities for actual verification are serving as barriers in research.[25]

As mentioned earlier, the EEW is expected to demonstrate its function most effectively for subduction-zone earthquakes. Among them, the major target would be the next Tonankai and Nankai Earthquakes, which are the largest-scale subduction-zone earthquakes. The current EEW is a *general-purpose* EEW targeting all earthquakes that clear the standards. Apart from this, however, it may be necessary to consider a *special* EEW that premises a special analysis method and a special reporting method that exclusively target the Tonankai and Nankai Earthquakes.

5-3 Approach from users' viewpoint

As discussed above, the Advance Notice is a service intended for expert users. Licensed business operators who have been approved by the Director-General of the JMA may add information which they have originally analyzed based on the information provided by the JMA. Particularly important additional information would be more precise seismic intensity based on detailed ground information. The JMA's predicted seismic intensity is based on ground information that has been averaged for a large area of about 10 km square, but actual ground conditions differ by each small land area, and it is no exaggeration to state that the conditions could even differ by each building site in some places. In the case of a high-rise building, the seismic intensity would differ by each floor. Thus, a company distributing Advance Notices will be able to differentiate their service from those of competitors by providing information that reflects individual customers' specific conditions. In this manner, the key to success of the business of providing Advance Notices would be to precisely respond to individual users' slightly differing needs for Advance Notices.

The frequency Alert issuance represents only about 1% of Advance Notice issuance. Nevertheless, the Earthquake Early Warning has become so well-known among the general public largely due to the transmission of Alerts. Conversely, people's opinion on Alerts tends to directly become their opinion of the EEW. Taking a look at news reports over the two and a half years since the launch of operation of the EEW from such perspective, the author receives an impression that mass media as well as people concerned in the EEW development focus too much on a single point—whether or not the EEW managed to reach recipients in time for the principal motion. As long as the function of issuing information immediately before ground motion is regarded as the biggest draw of Alerts, it is unavoidable that people's attention tends to be directed only to this point. As a matter of course, continued attempts should be made to extend the time allowance by working toward improving the analysis techniques and systems. However, such efforts cannot go beyond the limits of principle. Now that the Alert has outgrown its novelty, it is considered to be the time for thinking about realistic measures for using the Alert. For example, for near-field earthquakes where no time allowance can be expected, it would be better to shift the focus to the real-time nature of the Alert, rather than continue pursuing whether or not the Alert can be issued in time for the principal motion. This means to treat the Alert as part of ground-motion-detecting control systems. Ground-motion-detecting control systems have been used in various fields since before the introduction of the Alert, but now that the Alert is penetrating into society, it may be possible to introduce *control by the Alert* as a new usage. One such idea is to distribute control signals triggered by the Alert to each home by taking advantage of the digitalization of televisions.

At the same time, there are fields where general-purpose use of the Advance Notice and the Alert is unsuitable. An extreme example is a nuclear power reactor. Nuclear power reactors already have a ground-motion-detecting control system, but there are too many problems involved in applying *control by the Advance Notice or the Alert* to the system, at least at present. In such a case, it would be more desirable to construct an original control system for the reactor based on the concept of the EEW; that is, to install seismographs for the current ground-motion-detecting control system at distant locations from the reactor. In actuality, a scheme is already taking shape to install a seismograph network surrounding a reactor as well as to install seismographs at the bottom of wells of several thousand meters deep in order to gain a time allowance of around 2 seconds for inserting the control rods.

5-4 Improvement of the Tsunami Warning as a ripple effect

Development of the EEW is expected to promote improvement of the Tsunami Warning as a ripple effect. The Tsunami Warning, which was introduced based on the Meteorological Service Act of 1952, reached the level of a practical warning through its computerization in 1980. However, in the subsequent 1983 Nihonkai-Chubu Earthquake (M7.7) and 1993 Hokkaido Nansei-oki Earthquake (M7.8), the warning failed to reach coastal residents in time, and the number of deaths and missing persons combined reached 100 and 259, respectively. Since source locations along the Sea of Japan are close to the coast, tsunamis arrive in a very short time after earthquake occurrence. In the case of the Nihonkai-Chubu Earthquake, a tsunami arrived 7 minutes after the earthquake occurrence at the quickest, and in the case of the Hokkaido Nansei-oki Earthquake, 3 minutes after.[26] However, as short as it is, the arrival time is in the order of minutes, so compared with the fact that the EEW is dealing with a time allowance in the unit of seconds, the technical barrier is considered to be lower. The effects of improvements relating to quicker issuance of the EEW, including the reliability of the receipt, analysis, and communications of data, contribute to quickening the issuance of the Tsunami Warning, and such improvements of the Tsunami Warning are under way.

6 Summary

At the time when the EEW was introduced in society, there was a trend to regard the EEW as a business opportunity. At present, however, an analysis has even been made that many companies have withdrawn from the service of providing the EEW, and this has left a negative impression that disaster prevention business involves substantial risk.[27] On the other hand, it is a fact that the EEW has been welcomed by society as one of the few case examples in which seismic research achievement has been directly put to beneficial use in people's lives, and that the EEW has been penetrating into people's daily lives. With the actual conditions of the EEW gradually becoming clear, EEW businesses are entering a crucial stage where their viability will be tested. Indeed, a system using dedicated terminals with built-in seismographs has been developed and commercialized, taking advantage of the weakness of the EEW that it cannot reach the user in time in the case of a near-field earthquake.

In the same sense, while the EEW has received high expectations as if it will become the core of future earthquake disaster prevention measures,[28] there is a concern that expectations could swell excessively. It has been the norm for conventional disaster prevention measures that such expectations tend to overestimate the measure, and generate a large gap with the reality. It is natural in a sense that expectations grow in the development phase, but when the EEW has been operated to a certain extent, it needs to be evolved into a realistic measure based on its actual performance, while considering the significance and limits of the EEW. The following list summarizes the author's main opinions and proposals mentioned in this article with focus on the realistic positioning of the EEW.

(i) The Alert and the Advance Notice differ only in terms of the target scope of predicted seismic intensity, but the difference in their recipients (the general public or expert users) creates a large difference in the nature, effect, and usage of their information. When discussing the EEW, these two need to be considered separately.

(ii) The EEW involves regressiveness whereby the time allowance becomes shorter as the seismic intensity becomes larger. In actual instances, many people may experience that they could deal with ground motion with a seismic intensity of 4 due to receiving the Alert. The author holds a concern that such experience would lead to an established impression that such effect is always guaranteed.

(iii) Since the EEW has only been operated for two and a half years, it has not yet encountered an event where it could fully demonstrate its intended function. Through accumulation of experience, users in their respective standings need to learn the most effective use of the EEW, while understanding its characteristics and limits. Also, information on seismic intensity is extremely meaningful in the process where EEW recipients accumulate experience and deepen their understanding. Although the current Alert omits information on seismic intensity, it is desirable to also include information on predicted seismic intensity distribution while giving consideration on how it should be conveyed.

(iv) Serious damage that causes casualties generally occurs when the seismic intensity is 6 lower or greater. Although there are exceptions, in the case of an inland earthquake, the EEW cannot reach the recipients in time for ground motion with such seismic intensity. However, in the case of a subduction-zone earthquake, the EEW could generate a time allowance of 10 seconds or more. In particular, high expectations are held for the EEW's effect for the next Tonankai-Nankai Earthquakes for which a seafloor seismic observation network is being developed. It may be significant to develop different EEW specializing in these particular earthquakes.

(v) In the case of a large subduction-zone earthquake, not only the near-field ground motion, but also the long-period ground motion in distant alluvial plains and sedimentary basins, particularly the Kanto Plain, becomes a problem. Research on disasters caused by long-period ground motion has only been started, but in such a case, the EEW which can generate a time allowance of several tens of seconds is expected to demonstrate a substantial disaster mitigation effect.

(vi) Mass media and people concerned in the EEW development focus too much on whether or not the EEW managed to reach recipients in time for the principal motion. Even in the case where the EEW does not reach the recipients in time, attention should be paid to the real-time nature of the Alert, in other words, that the Alert is transmitted almost at the same time as the earthquake occurrence. The current Alert does not employ the concept of automatic control, but in the sense of complementing the weakness of the Alert that it cannot reach the recipients in time for the strong ground motion of an inland earthquake, it may be necessary to adopt the concept of *control by the Alert* in the future.

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