A STUDY ON EXPECTED DISTRIBUTION OF LEAD TIME BY EARTHQUAKE EARLY WARNING

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ABSTRACT: The 2008 Iwate-Miyagi Inland Earthquake on June 14, 2008 was the first case that EEW could be successfully broadcasted before the arrival of strong tremors. However, the warning could not be provided before strong tremors to some areas near the hypocenters. The number of earthquakes that EEW was announced since October, 2007 is too limited to evaluate the effectiveness of EEW properly. In this research, expected lead times before S-waves were analyzed based on the assumption that EEW system had been operated during 1923 to 2007. In addition, the effect of increasing seismometers in the future was also simulated. Based on the results, regional characteristics of expected lead times of EEW and their damage mitigation effect in each region were revealed, and future strategies for making the best use of EEW were discussed.

Key Words: Earthquake Early Warning, Lead Time, Mitigation Strategy

INTRODUCTION

It is said that seismic activity around Japan is increasing. Japan has a high probability of big earthquakes such as Tokyo Metropolitan Inland Earthquake with magnitude around 7, Tokai, Tonankai, and Nankai Earthquakes with magnitude 8 or more in the near future. The Japan Meteorological Agency (JMA) has launched earthquake early warning (EEW) system for the public since Oct. 1st, 2007. This is a new system that quickly analyses seismic wave data observed by seismometers near an epicenter and provides prompt alerts which may reach people before the arrival of strong tremors (S-waves).

The 2008 Iwate-Miyagi Inland Earthquake on June 14, 2008 was the first case since October 2007 that EEW could be successfully broadcasted before the arrival of S-waves. The warning was widely provided by television, the radio and mobile phones. At the earthquake, however, the warning could not reach before S-waves in some areas near the epicenters. This situation was regarded as a failure of EEW among the general public although it was due to technological limitation of EEW methods in case of inland earthquakes. After the earthquake, some mass media questioned the meanings of EEW and unfortunately, this led to negative understanding on effectiveness of EEW among some of the general public.

According to JMA, EEW had announced to the public 17 times. The number of EEWs which were succeeded in being available before strong tremor is limited. In addition, EEW for advanced users had announced 111 earthquakes until Octber 2010 since it started. These numbers are statistically too limited to decide the effectiveness of EEW. It is important to provide quantitative data about

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expected lead time that EEW could provide before future earthquakes in order to promote proper understanding on its merits and limitations.

Technologies for announcing EEW are still renovating (Meguro, 2007). Figure 1 illustrates three approaches for making better use of EEW. The first approach is proliferation of seismometers, such as increasing the number of seismometers and densifing their network, which leads to the prompt detection of an earthquake. The second is minimization of time before the warning, such as data transmissions and determination of a focus and magnitude of an earthquake. The last approach is response; in other words, how people can prepare for a strong tremor during lead times. Software approaches such as preparing manuals, are one part of the response. On the other hand, hardware approaches such as automatic response systems, play the other part.

In this study, using the past earthquakes occurred during 1923 to 2007, expected lead times before S-waves were analyzed on the assumption that the current EEW system had been operated before those earthquakes. According to the results, regional characteristics of expected lead times of EEW and their damage mitigation effect were revealed. In addition, the effect of increasing seismometers such as Ocean-bottom seismometers or Hi-Net by National Research Institute for Earth Science and Disaster Prevention (NIED) in the future was also simulated. Considering the results obtained in both current and future cases, future strategies for making the best use of EEW were discussed.

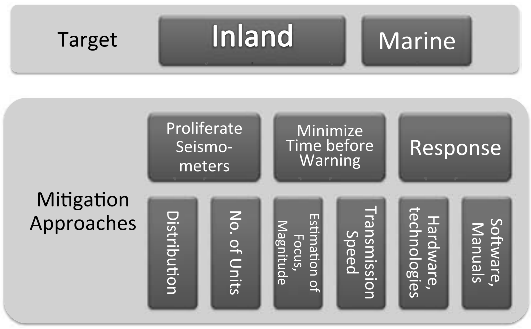


Figure 1. Target and mitigation approaches considered in this study

METHOD FOR CALCULATION

Data of earthquakes used

In this rstudy, data of 62,127 earthquakes with magnitude 4 or more occurred during 1927 to 2007 listed in “Report on Earthquakes and Volcanoes (Catalog)” by JMA was used. The number of earthquakes that EEW was announced since October, 2007 is too limited to evaluate the effectiveness of EEW properly. Then, the data of the past earthquakes was used in order to understand expected lead times that could be provided by EEW in future earthquakes.

Table 1. The number of earthquakes for calculation

Year	M4	M5	M6	M7	M8	Total
1923-1966	6,505	2,673	620	348	7	10,153
1967-1980	4,637	1,496	287	83	5	6,508
1981-1990	5,911	3,607	459	12	0	9,989
1991-2000	13,660	6,772	657	22	1	21,112
2001-2007	9,074	4,799	482	28	2	14,385
Total	39,787	19,347	2,505	493	15	62,147

Locations of seismometers

JMA uses 205 seismometers for providing initial alert of EEW as of November 2010. According to JMA, 774 seismometers of Hi-Net by National Research Institute for Earth Science and Disaster Prevention (NIED) are currently used only to double-check the location of the estimated hypocenter and the magnitude of a coming earthquake. Figure 2 shows the distribution of 205 JMA seismometers, and Fig. 3 shows that of Hi-Net. In the chapter 3, locations of JMA seismometers were used. The fourth chapter simulated the effect of increasing seismometers and 774 seismometers of Hi-Net were used for the calculation.

Figure 2. Distribution of JMA seismometers

Figure 3. Distribution of Hi-Net seismometers

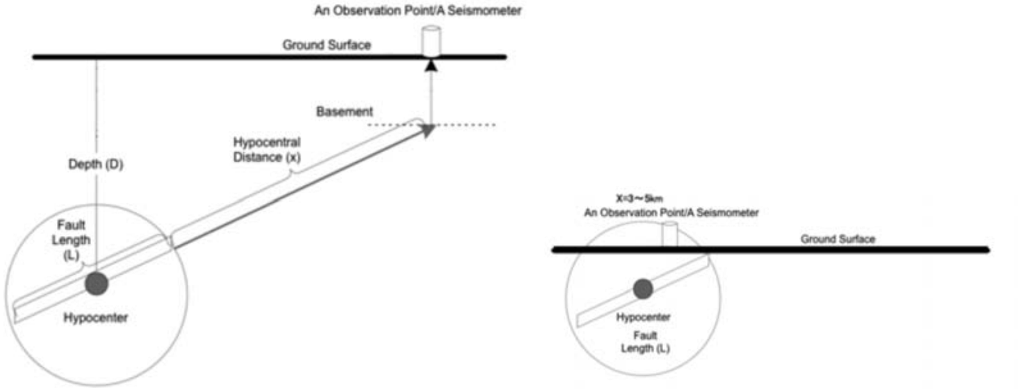
Method for estimating lead time and seismic intensity

Japan has 47 prefectures and totally 1955 local municipalities under prefectures. This research estimated lead times and expected seismic intensities of the 62,147 past earthquakes at 1,955 local municipality offices all over Japan based on the assumption that EEW had been operated before those earthquakes. We regard the locations of 1955 local municipality as observation points. The procedure for estimation is same as the method currently used by JMA (2010).

When an earthquake occurs, seismometers near its hypocenter detect ground vibration, and the location of hypocenter is estimated by using the data observed by these seismometers. Figure 4 illustrates a model of obtaining the distance between a hypocenter and the nearest seismometer or an observation point. The distance was calculated using equations, eqs. (1) to (9). Here, all the seismometers were assumed to be located at the ground surface because their depth was negligible for obtaining the distance to the hypocenter. Hypocenters were treated as fault planes as shown in Fig. 4 (a). In case that half of the fault length was longer than the distance between the hypocenter and an observation point / the nearest station, the distances were set to be 3km as shown in Fig. 4 (b).

Next, expected times for P-wave to travel to the nearest seismometer and for S-wave to strike each observation point were calculated. Based on these time differences, lead time provided by EEW before the arrival of S-wave at the observation point was obtained. In the real procedure for announcing EEW, analysis for estimating the hypocenter takes several seconds, but this time lag was not considered in this paper in order to estimate the maximum effectiveness of EEW. The velocities of P-wave and

S-wave varying according to depth level were used following the table by JMA.



(a) Case Where Distance Between An Observation Point / A Seismometer Is Smaller Than A Half of Fault Length

(b) Case Where Distance Between An Observation Point / A Seismometer Is Bigger Than A Half of Fault Length

Figure 4. Calculation Model for Deciding The Distance Between A Hypocenter and An Observation Point / The Nearest Station

$$a = \cos\phi \cdot \cos\theta \tag{1}$$
$$b = \cos\phi \cdot \sin\theta \tag{2}$$
$$c = \sin\phi \tag{3}$$
$$d = \cos\phi' \cdot \cos\theta' \tag{4}$$
$$e = \cos\phi' \cdot \sin\theta' \tag{5}$$
$$f = \sin\phi' \tag{6}$$
$$x = \sqrt{\{R \cdot \arccos(a \cdot d + b \cdot f + c \cdot e)\}^2 + D^2} - L/2 \quad (0 \le x) \tag{7}$$
$$x = 3 \quad (x < 0) \tag{8}$$
$$\log L = 0.5M - 1.85 \quad \text{(Utsu: 1977)} \tag{9}$$

θ, ϕ: Latitude, Longitude (rad), D: Depth(km), R: Radius (km), x: Minimum distance to fault(km), L: Length of fault

Then, expected seismic intensities at 1955 local municipality in case of the 62147 past earthquakes were calculated using equations of eqs. (10) to (13).

$$M_w = M_{JMA} - 0.171 \tag{10}$$
$$\log(PGV_{600}) = 0.58M_w + 0.0038D - 1.29 - \log(x + 0.028 \cdot 10^{0.50M_w}) - 0.002x \tag{11}$$
$$PGV = ARV_i \cdot PGV_i (= ARV_i \cdot 0.90 \cdot PGV_{600}) \tag{12}$$
$$I_{INSTRA} = 2.68 + 1.72\log(PGV) \pm 0.21 \quad (4 < I_{INSTRA} < 7) \tag{13}$$

M_w: Moment magnitude, M_{jma}: JMA magnitude, PGV_{600}: Maximum velocity at engineering bedrock (S-wave velocity is 600 m/s), PGV_i : Maximum velocity at land surface, ARV_i : Amplification factor between land surface and 30m depths

Method for evaluating damage mitigation effects

In Japan, earthquakes are categorized to 2 types; inland and marine earthquakes according their location of epicenters as described in Fig.1. As for increase of inland earthquakes, lead times are generally small because time lags between S-wave and P-wave are expected to be short. On the other hand, lead times of marine earthquakes whose epicenters are in the ocean might be much longer. Therefore, this research treats these two earthquake types separately.

This research estimated lead times and expected seismic intensities of the 62,147 past earthquakes with magnitude 4 or more at 1,955 local municipality offices in Japan. These results were summarized to the number of earthquakes in each prefecture according to the expected lead times and seismic intensities. The past earthquakes included both marine and inland earthquakes. The trends of expected lead time in both marine and inland earthquake types in each prefecture were analyzed. Moreover, regional characteristics of expected lead times of EEW and their damage mitigation effect were evaluated in each prefecture.

As mentioned in the chapter 1, proliferation of seismometers is vital for EEW improvement. Since only 205 seismometers are currently used for the initial alert of EEW, the distance between a hypocenter and a seismometer might be long in some area. This possibly causes a late detection of a future earthquake. If seismometers are proliferated, lead time generally increases because of the minimization of the distance. This research clarified the effectiveness of the proliferation of seismometers. The cases, in which the number of seismometers was increased and their network was densified, were simulated. Comparing the results of these cases with the current situation, the effectiveness of lead times was evaluated.

ANALYSIS OF EXPECTED LEAD TIME OF EEW AT PAST EARTHQUAKES

In this chapter, lead times for the past earthquakes during 1923-2007 were analyzed based on the assumption that EEW had been operated before those earthquakes.

Expected lead time distribution of EEW in each prefecture

The lead times and seismic intensities of EEW at the past earthquakes were calculated at 1,955 local municipality offices as explained in the chapter 2. Outcomes of calculations for municipalities in one prefecture were added up to be data of one prefecture. When several municipalities in one prefecture record shaking at an earthquake, the largest seismic intensity among the municipalities and its corresponding lead times were plotted on the figure. Figure 5 shows the distribution of the expected lead times in Kanagawa Prefecture. The horizontal axis means lead time, and the vertical axis shows the cumulative numbers of earthquakes whose lead times are more than the value on the horizontal axis. Cumulative curves for expected lead times were plotted according estimated seismic intensities from 4 to 7. The negative value of the horizontal axis infers that S-wave strikes before an EEW announcement. The seismic intensity 4(a) means the curve for EEW whose seismic intensity is simply estimated 4. The seismic intensity 4(b) means the curve whose maximum intensity outside the prefecture is 5- or more although the intensity inside that prefecture is 4.

Analysis on regional characteristics of expected lead time of EEW

Japan is surrounded by 4 plates. Distances from ocean trenches could affect regional characteristics of the expected lead times in each prefecture differently. According to the expected lead times in each prefectures, 47 prefectures were classified into four typical types; Kanagawa, Iwate, Nagano, and Hokkaido's types.

First, Kanagawa type has relatively long lead times among all the prefectures. The cumulative number of earthquakes moderately decreased according to the length of lead time as shown in Fig.5

because the effect of marine earthquakes with long lead times was more strongly reflected than that of inland earthquakes. Yamanashi, Osaka, Mie and Tokushima Prefectures were similar to this type. Osaka had longer lead times in case of inland earthquakes because of soft surface soils below Osaka area led to big seismic intensity at remote earthquakes with big magnitude. In this case, much longer lead time could be provided to respond against the coming shaking.

Second is Iwate type. Its expected lead times are not as long as Kanagawa type because Iwate prefecture is located near trenches. As shown in Fig.6, the cumulative number of earthquakes rapidly decreased as lead time was between 0 to 10 seconds. Fukushima Prefecture was also classified in the same type because curves of the lead time less than 20 seconds were especially similar to Iwate type. In prefectures with these characteristics, damage mitigation approaches within 10 seconds should be arranged.

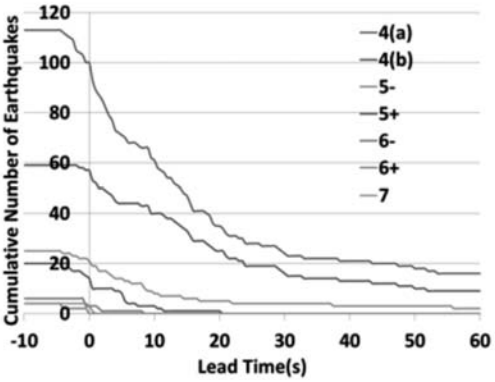


Figure 5. Expected distribution of lead times in Kanagawa prefecture

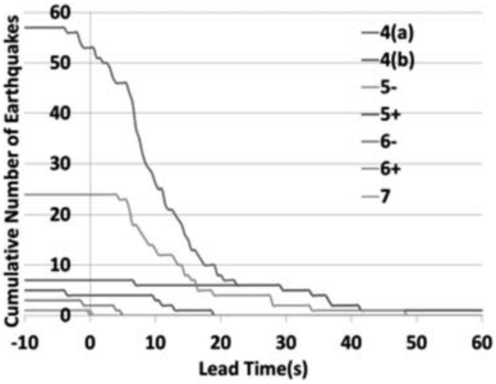


Figure 6. Expected lead times of EEW in Iwate prefecture

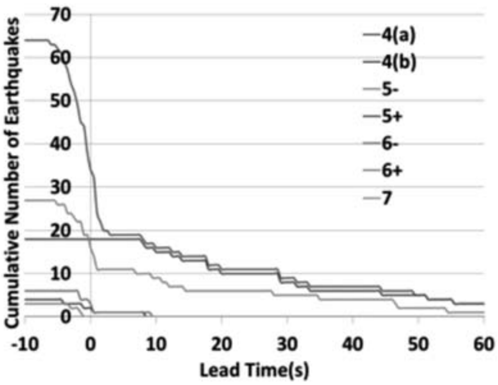


Figure 7. Expected lead times of EEW in Nagano prefecture

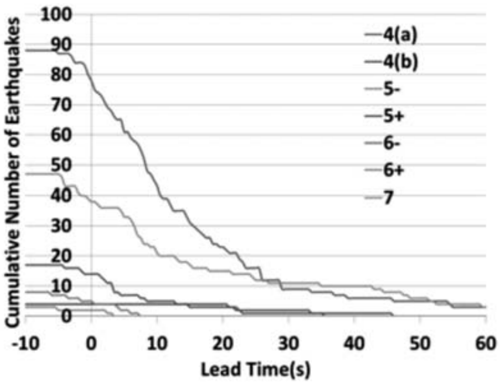


Figure 8. Expected lead times of EEW in Hokkaido prefecture

Third is Nagano type. In this case, long lead time can not be expected as shown in Fig.7 because of frequent occurrence of inland earthquakes. In fact, 90 were inland earthquakes while the total number of earthquakes affecting Nagano Prefecture was 104; about 87% of the earthquakes with seismic intensities 4 or more were inland types in this area. Therefore, the curves dropped drastically around lead time 0 second because hypocenters were too close to the observation points. Consequently, damage mitigation approaches including automatic response systems, which are possibly applicable with in seconds, are extremely necessary to cope with these inland earthquakes. On the other hand, the gently decreasing line after that drop indicates this type also has long lead times in case of large earthquakes which occurred far away.

Finally, fourth is Hokkaido type. Because there is enough distance from trenches and troughs to obtain long lead time of EEW, the curves of this type moderately decreased from the top at lead time 0 second as shown in Fig.8. 113 of total 163 earthquakes which recorded seismic intensities 4 or more, occurred in ocean area, and the most of them had long lead times such as 30 seconds or more. All of the earthquakes with seismic intensities 5- were located at the boundary between North America plate and Eurasian plate. This characteristics show the effectiveness of damage mitigation approaches taking 10 seconds or more.

EVALUATION OF EFFECT OF USE OF MORE SEIMOMETERS FOR EEW

Effect of use of ocean-bottom seismometers

In October 2008, JMA started to operate extra 5 ocean-bottom cable seismometers in Tokai and Tonankai area. In this section, the effect of using new 5 ocean-bottom seismometers in addition to the existing 205 seismometers was evaluated. Table 3 and Figure 9 show the locations of new ocean-bottom seismometers reported by JMA (2008).

Installing ocean-bottom seismometers aimed to increase lead times of EEW at the future earthquakes. In order to evaluate these effects, an index "E" was proposed to quantify the increase of lead time by using new ocean-bottom seismometers. It corresponds to the difference of the total area of lead time curves with/without ocean-bottom seismometer. Here, curves $f(t)$ of lead times in expected lead times figures were used.

Table 3. Locations of Ocean-Bottom Seismometers

Seismometers Name	North Latitude	East Longitude	Altitude
TT1OBS	33.62	136.78	−2068m
TT2OBS	33.73	137.03	−2100m
TT3OBS	33.86	137.40	−1000m
TT4OBS	34.01	137.54	−1836m
TT5OBS	34.25	137.72	−1019m

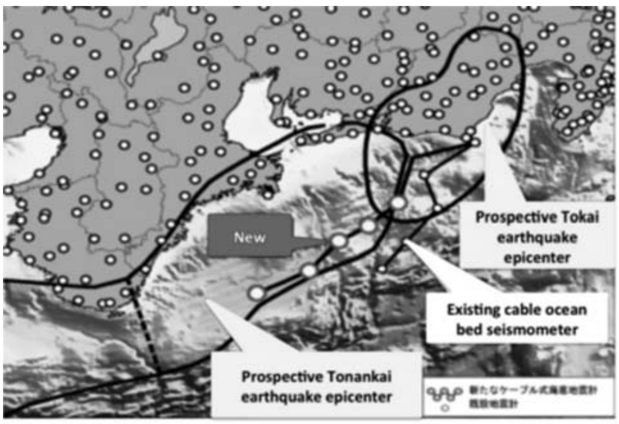


Figure 9. Locations of ocean-bottom seismometers

$$E = A - A_0 \qquad (14)$$

$$A = \int f(t)\,dt \qquad (15)$$

A_0 : Area of lead time curves with the current systems without ocean-bottom seismometer, A : Area of lead time curves with ocean-bottom seismometers.

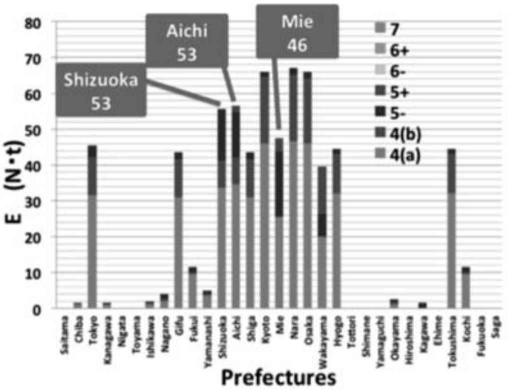


Figure 10. E Value in Each Prefecture with Ocean-Bottom Seismometers

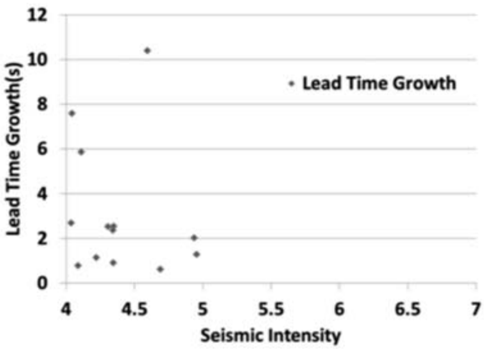


Figure 11. Lead time growth in Shizuoka

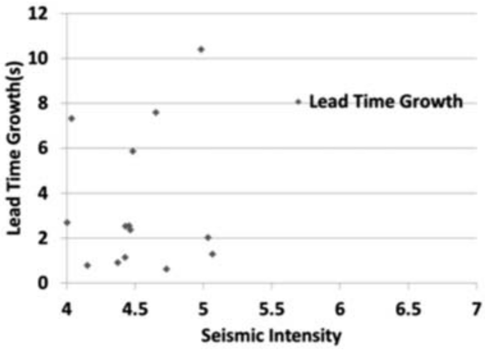


Figure 12. Lead time growth in Mie

Figure10 shows the value of index E for each prefecture in case that the ocean-bottom seismometers were used in addition to the current JMA ones. In the prefectures near by Nankai Trough such as Shizuoka, Aichi, and Mie, the values of E were big especially with the seismic intensity 5- or more. Since these prefectures have shorter distance from the trough than the other prefectures, installing ocean-bottom seismometers is expected to have positive effect against strong earthquakes. Figure 11 shows the relationship between expected seismic intensities and the growth of the lead time that were achieved at the earthquakes by using ocean-bottom seismometers in Shizuoka Prefecture. In Fig.11, the total number of earthquakes with intensity 5- is 13, which is almost same as the other prefectures whose values of E were high. The highest growth of lead times by installing ocean-bottom seismometers was over ten seconds at the earthquake whose expected intensity in Shizuoka was 5-. Compared to the lead time growth in Mie as shown in Fig.12, most dots only slide to the right because of the distance decay with seismic intensities. Both prefectures are suffered from the 1944 Tonankai earthquake and the 1946 Nankai earthquake. These earthquakes were magnitude 7.9 and 8.0. However, both figures do not show the lead time growth in these earthquakes because added ocean-bottom seismometers are not so critically near by the epicenters of these two earthquakes.

Effect of using Hi-Net

Proper response to EEW is different according to the lead times available. If lead time before S-wave is few seconds, only automatic response systems could reduce the damage due to a coming earthquake. For example, automatic system for protecting important facilities, shutting down gas supply, stopping transportation systems, etc. could be effective. If about 10 seconds is provided as lead time, there is possibility for people to take some actions to protect themselves. As the lead time increase to be more than 10 seconds, more complicated actions for protecting properties and people become possible. Installing more seismometers aims to increase lead time at the future earthquakes. Increasing short lead time might have more impact than increasing long lead time; for example, growth of lead time from 0 to 5 seconds could be more meaningful than that of lead time from 30 to 35 seconds. It implies that the meaning of index E could be different according to the lead time. Then, three types of index E were proposed to understand the detail impact by installing new seismometers. They are $E_{0\text{-}5}$ that corresponds to the change of lead time curve during 0-5 seconds, $E_{0\text{-}10}$ during 0-10 seconds, and $E_{10\text{-}}$ during the lead time more than 10 seconds. The lead time is more demanded than the one of longer lead time.

In this section, the effect of use of Hi-net was evaluated. Hi-Net has 774 seismometers operated by NIED. Index E for each prefecture was calculated by eqs.(14) and (15) in case that Hi-Net was used in addition to 210 seismometers including JMA and ocean-bottom seismometers.

Index $E_{0\text{-}5}$, $E_{0\text{-}10}$, and $E_{10\text{-}}$ for each prefecture were calculated in case that Hi-Net was used in addition to 210 seismometers including JMA and ocean-bottom seismometers. As a result, three typical types were observed; Kanagawa, Ibaraki, and Saitama types. Figure 13 shows the value of Index $E_{0\text{-}5}$, $E_{0\text{-}10}$, and $E_{10\text{-}}$ of three prefectures according to the seismic intensity. The numbers of total earthquakes in each prefecture are shown in the parentheses under prefecture names.

First, the Kanagawa type shows high $E_{0\text{-}5}$ and $E_{0\text{-}10}$; especially, $E_{0\text{-}5}$ was high enough to dominate the high percentage of $E_{0\text{-}10}$. It is said that use of Hi-Net will provide more opportunities whose lead times are 0 to 5 seconds. These trends were observed not only for the earthquakes with intensity 4 but also for the earthquakes with seismic intensity 5- or more. In Kanagawa Prefecture, adding Hi-Net to the current EEW network was considered highly beneficial because it could totally achieve big growth of indexes E. Considering future use of Hi-Net, implementation of automatic response system had better be promoted in order to make better use of expected lead time.

Second, Ibaragi type shows the characteristics that $E_{0\text{-}10}$ and $E_{10\text{-}}$ are high instead of $E_{0\text{-}5}$. Use of Hi-Net will provide more opportunities whose lead times are more than 5 seconds. In order to use the benefit of Hi-Net, software approaches including human response might be effective as well as hardware approaches.

Third, Wakayama type has low value in each indexes E. The result shows that Hi-Net does not generally affect the lead time 0 to 60 even though the total number of earthquakes is 62. Therefore, the proliferation of seismometers needs more investigation on where to install, otherwise damage mitigation approaches can not improve.

In this chapter, index E evaluated the effect of increasing the lead time by using ocean-bottom seismometers or Hi-Net. In order to understand the effect of proliferations of seismometers, referring to both the expected lead time distribution and the value of index E is necessary. Based on the effect of installing Hi-Net on EEW damage mitigation approaches suitable for each prefecture were proposed in this section.

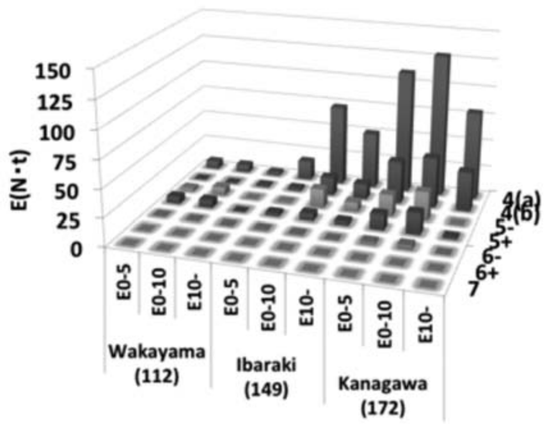


Figure 13. E value in Wakayama, Ibaraki, Kanagawa with Hi-Net

CONCLUSIONS

In this study, expected lead times of EEW were analyzed using the past earthquakes during 1923 to 2007 based on the assumption that EEW had been operated before those earthquakes. Based on the results obtained in the study, regional characteristics of expected lead times and their damage mitigation effects were revealed.

In addition, method for evaluating the effect of use of more seismometers was proposed defining three kinds of indexes E. Not only the currently-used 205 JMA seismometers, but also 5ocean-bottom seismometers and Hi-Net ones were taken into account for estimation. Finally, approaches to make suitable strategies for each area reflecting the characteristics of expected lead times were proposed.

At first, there are mainly four types in expected lead times with the current 205 JMA seismometers. Kanagawa and Hokkaido types expectedly have long lead times and are able to plan damage mitigation approaches sparing long time. However, in a hand, Kanagawa type does not suffer from earthquakes with intensity 5- or more. On the other hand, Hokkaido type has many 5+ earthquakes. On the contrary, both Iwate and Nagano types show shorter lead times even if each of them suffers from each type of earthquakes; inland and marine. In prefectures with these characteristics, damage mitigation approaches which are applicable within seconds should be considered.

Second, the effectiveness of ocean-bottom seismometers was analyzed using index E. Prefectures near by Nankai trough benefitted from these additional seismometers. Especially Shizuoka, Mie, and Aichi were so affected by these seismometers that they could maintain 10 seconds or more lead time growth.

Third, the effect of Hi-Net installing to EEW were studied. In this case, index E are taken apart to three; E_{0-5}, E_{0-10}, E_{10-}. Depending on the amount of indexes E, the effectiveness on expected lead times in the future was analyzes, and strategies considering this prospect were mentioned in this study.

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