# AVAILABLE WARNING TIME FOR EMERGENCY RESPONSE IN SENDAI CITY, JAPAN AGAINST MIYAGI-OKI SUBDUCTION EARTHQUAKES BASED ON NATIONAL AND REGIONAL EARTHQUAKE EARLY WARNING SYSTEM

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**ABSTRACT :**

Sendai, located in northeastern Japan, is the biggest city in the Miyagi prefecture has about one million population and suffered severe damage by subduction zone earthquakes in history. Last one was, 30 year before, 1978 Miyagi- ken oki earthquake with M 7.4. The occurrence of huge events in this prefecture has the average of 37.1 year and 6 year standard deviation. Therefore this seismically vulnerable city needs urgent strong motion prediction and reliable Earthquake Early Warning Systems. The City is preparing now for Miyagi-ken offshore earthquake and it is crucial to inform society about the warning time of a probable upcoming earthquake so that precautionary actions can be taken by the individuals, government or the companies. This paper describes considerations about various warning time and differences of time intervals between onset time of P-wave to P-wave, P-wave to S-wave, P-wave to PGA, S-wave to S-wave and S-wave to PGA. Their meaning and importance are discussed according to different warning level for two locations. Warning times are first calculated depend on travel time tables of theoretic P- and S- wave velocities and then based on recorded accelerograms with usage K-net. The study indicates that Sendai has 17.3 second in average with 6.4 second standard deviation before the strong shaking reach the city.

**KEYWORDS:** Warning time, Earthquake early warning systems, Miyagi-oki earthquake

## 1. INTRODCUTION

Japan is subject to high seismicity due to subduction zone earthquakes. Northeastern Japan lies atop the overriding plate that moves approximately 10 cm/year. In the northeastern Japan subduction zone, many shallow earthquakes occur, mostly on reverse faults that strike nearly parallel to the trench axis along the plate boundary underneath the Pacific Ocean (Okada et al. 2001). The frequent seismic activity forced scientist and engineers to study earthquake phenomena not just Japan but as well as other earthquake active zones such as California and Taiwan. With parallel to this, the earth structure and geophysics studies with related to seismology enormously improved in last century. Meanwhile, seismology has become an important function of evaluating earthquake hazard. Nowadays seismic risk, basically meaning reduction of the impact of earthquakes on the society, has been investigated from several aspects. Moreover due to new improvements on real-time seismology, there is an urgent need for evaluating the seismic risk from this point of view.

Real-time based seismology has enhanced with the improvements in communication technology especially in last decade. Earthquake early warning systems emerge from dream to publically utilization stage in the active seismic zones such as Japan, Mexico, Turkey, and Taiwan. Japan is leading the technologic improvements and has one of the most reliable EEWS in the world with adequate high dynamic range and bandwidth instruments. This system has finished infrastructure all over the country and were testing it since July 2002 (Horiuchi et. al. 2005). Big step was made in October / 2007 when JMA started to serve source information, time of impending S wave and JMA intensity to public and private companies. Although this information is valuable for EEW application, actually it is not adequate to make proper actions for advanced engineering usage. Therefore, Motosaka et. al. (2008) developed a regional warning system in Miyagi prefecture which support the national

EEWS, furthermore enhances the accuracy of real-time ground motion estimation not just for seismic intensity (like peak ground acceleration and peak ground velocity, Kuyuk and Motosaka 2008, Kuyuk et. al. 2008) but also spectra and waveform in order to apply advanced engineering applications.

The authors are using JMA/NIED Japan national EEWS since 2006 and our developed independent regional warning system increase reliability and supplementing the national EEW configuration. The system has multi purposes such as structure health monitoring, real time application for structures and is described in Motosaka et. al. (2008). It is the fastest EEWS that can serve waveform with variable packets (set for this application as 0.2 sec packet) to client with transmission speed less than 0.2 sec for each packet. Two separate systems are integrated to be mutually beneficial for the advanced engineering application purposes. The configuration of the overall system is shown in Figure 1, circle symbols represent the regional configuration, triangles are the K-net along the main towns in the area and reversed white triangles are the High Network data (national EEWS). Based on our experience, the national EEWS information reaches the Disaster Control Research Center (Tohoku University, Sendai) in 5.5 sec average after detection of an earthquake in the nearest point. This delay reflects the transmission delay that is caused due to the communication process time between Sendai and Tokyo where the JMA/NIED center is located. Therefore, in our hybrid approach the source information is known after detection of earthquake in 5.5 sec and then further information and calculations are provided by our regional system.

Seismic early warning systems provide warnings of forthcoming danger on rapid estimates of the earthquake source parameters; warning systems utilize the capability of modern real-time systems to process and transmit information faster than seismic wave's propagation (up to 8 km/s). The possible warning time is usually in the range of up to 70 seconds (in Mexico), depending on the distances between seismic source, seismic sensor and user sites. The available warning time of an earthquake ($\Delta t$) can be defined by the time interval between the detection of the P-wave by a sensor in near field and the arrival of energy carrying S-waves at the user site. The epicentral distance $E_{sensor}$ of the first detection site, $E_{user}$ of the user site and focal depth of earthquake $z$, the warning time $\Delta t$ can be estimated by

$$\Delta t = \sqrt{\left(E_{user}^2 + z^2\right)}\Big/ v_s - \sqrt{\left(E_{sensor}^2 + z^2\right)}\Big/ v_p - t_{decision} - t_{transmission} \qquad (1.1)$$

where $v_p$ and $v_s$ are the P and S-wave average velocities and $t_{decision}$, $t_{transmission}$ are the time needed for decision of data processing and data transmission times. These two times are separated here to indicate that transmission is more related to technological problem where decision time is related how the decision maker wants to sure the level of earthquake destructivity.

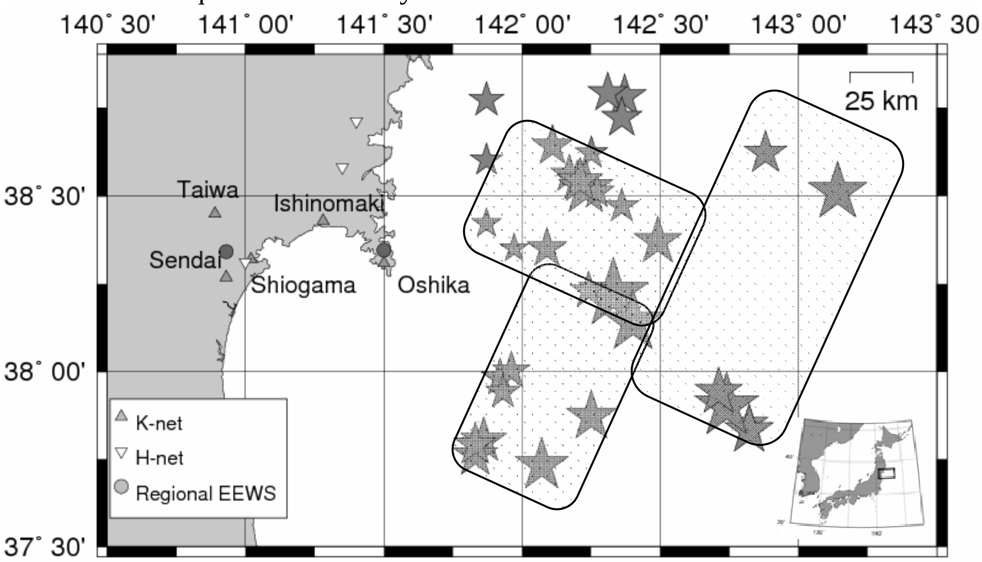


Figure 1 Miyagi Prefecture And Miyagi Ken Offshore Earthquake Epicenters

Therefore, in this study, the available time analysis against Miyagi-ken offshore earthquakes is investigated. It is believed that this study can contribute valuable information to society and seismic hazard studies. Firstly available time analysis is performed depend on travel time tables between two cities Oshika and Sendai. Furthermore, we calculated the times depend on waveforms recorded by K-net networks in the same area which we believe the results are less biased than theoretical time table based information.

## 2. SUBDUCTION EARTHQUAKES IN MIYAGI PREFECTURE

Both systems are deployed in Sendai where Sendai basin is located in northeastern Japan. Sendai city, the biggest city in this basin has about one million populations and suffered from severe damage by subduction zone earthquakes in history. Last one was, 29 year before, 1978 Miyagiken-oki earthquake with M 7.4. The occurrence of huge events in this prefecture has the average of 37.1 years and 6 years standard deviation. Therefore this seismically vulnerable city needs urgent strong motion prediction and reliable Earthquake Early Warning Systems. The City is preparing now for Miyagi-oki earthquake and it is crucial to inform society about the warning time of a probable upcoming earthquake so that precautionary actions can be taken by the individuals, government or the companies. Namely society, government and private organizations asking for how many seconds they have before the earthquake information reach them.

### *2.1 Estimation Based On Travel Time Tables*

Seismologists have been observing earthquakes for many decades. Through repeated observations travel time tables for different waves and paths (P, S, PS, PP etc.) through the earth were obtained. These travel time tables show the times the waves take to go between the source and the seismic station along different paths. Now nearly each country has its own travel time table as well as Japan. In this part, travel time tables were used to produce earthquakes in extended possible Miyagi-ken offshore earthquakes. A window bounded by 37.5N-38.8N latitude and 141.7-143.5 degrees longitude was used. Depend on point source assumption earthquakes sources were located time interval between 0.1 degree (about 11 km) in latitude and longitude and 20 to 70 km in depth with 10 km interval depths (six layers, Figure 2). Two stations in the region MYG011, Oshika, the nearest inland point of coastline in the prefecture and MYG013, Sendai city were investigated from the available time point of view, most likely earthquakes in Miyagi-ken Offshore. The time difference onset of P-wave in two cities is plotted in Figure 3 where S-waves are plotted in Figure 4. The first former figure indicating that the shallow or near earthquakes to Oshika (less than 200km) many earthquake will be detected in both sites before the source information of national EEWS reach the Sendai city. Moreover the latter is indicating, even there is 9 to 10 seconds average after detection of S-wave in Oshika to reach Sendai city. If it is assumed to be that peak ground acceleration comes soon after the S-wave, there will be a warning time even after detecting the PGA in Oshika. This information can be absolutely reduce the false warning due to limited estimation depend on initial ground motion.

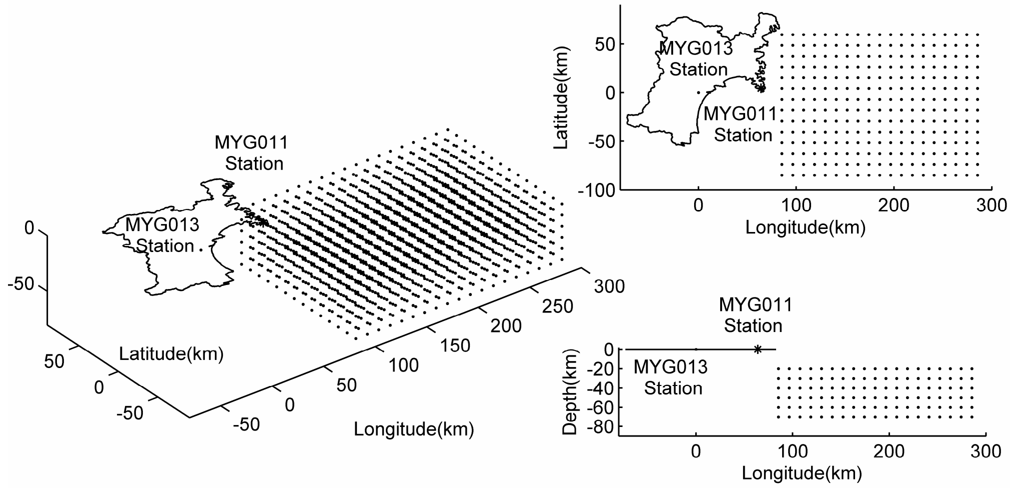



Figure 2 Located point source earthquakes in the offshore Miyagi prefecture

The available times between these two cities according to Eqn. 1.1 with the assumption of transmission and process time zero, are plotted in Figure 5. The available time is a function of hypocentral distance. The time difference of the same hypocenter shows whether the assumption point source is in the corner of source matrix or in the middle. In any case, the minimum available time seems to be about 13 seconds and maximum is the 32 seconds where the average is the around 24 seconds. If the average of warning time of national EEWS is subtracted to these times there will be minimum 7 seconds for the nearest earthquake where the average of available time will be around 20 seconds. One of the semiconductor companies in Miyagi Prefecture says that they have capability to stop product line in the factory in three seconds. With this information they will be able to stop the production in any case of Miyagi-ken offshore earthquakes regardless of false alarms.

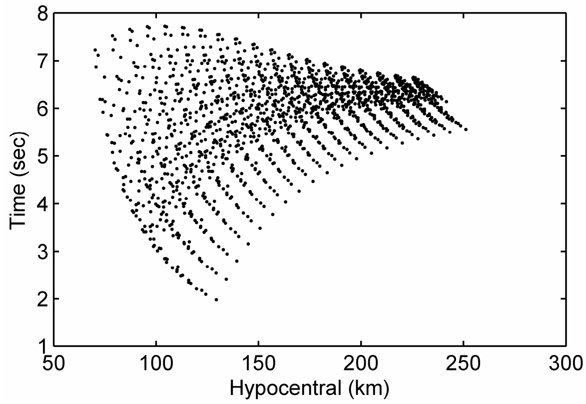


Figure 3 Time difference of P-P wave onset for Sendai and Oshika cities

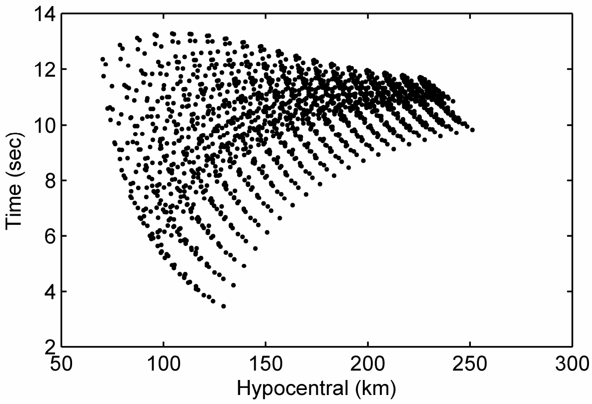


Figure 4 Time difference of S-S wave onset for Sendai and Oshika cities

### *2.2 Estimation Based On Recorded Accelerograms*

Recordings of 38 earthquake events in Miyagi-oki were used for available time analysis. The earthquakes used in this study were recorded by the K-net at the following stations: Oshika (MYG011) and Sendai (MYG013) at Miyagi Prefecture. A window bounded by 37.5N-38.8N latitude and 141.7-150 degrees longitude was used. Earthquakes that occurred in the region of eastern Miyagi from January 1996 to September 2007 are shown in Figure 1.

The range of the earthquake parameters was limited to 4.1-7.2 for magnitude (M), 27-173 (km) for epicenteral distance (E), and 14-99 (km) for depth (D). This limitation was adopted in order to achieve high quality in the result and improve correctness. The specification of earthquakes and input data are shown in Table 1. Here I present estimates of the warning times that would be available for far sites (inner land of Miyagi prefecture) against Miyagi oki earthquakes with the usage of hybrid EEWS. The warning times were calculated using the existing seismic network (K-net) geometry in the region depend on the actual records from 1996 to 2007. This section describes considerations about various warning time and differences of time intervals between onset time of P-wave to P-wave, P-wave to S-wave, P-wave to PGA, S-wave to S-wave and S-wave to PGA. Their meaning and importance are given and discussed according to different warning level for two locations. Calculated warning times are based on recorded accelerograms with usage of national and regional Earthquake Early Warning Systems.

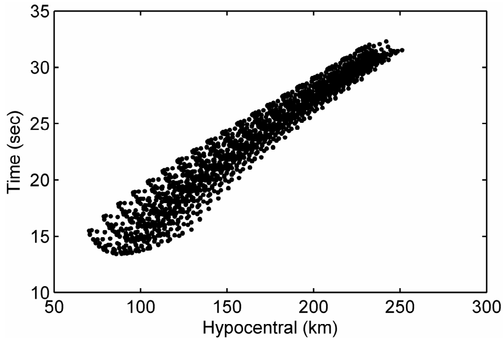


Figure 5 Available time between Oshika and Sendai cities

Table 1 Time difference of stations MYG011-MYG013

| No | Date | P-P | P-S | P-PGA | S-S | S-PGA | PGA-PGA | Epi. | Depth | Hyp. | PGA | Mag. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0008281720 | 5.47 | 17.99 | 20.87 | 9.29 | 12.17 | 13.42 | 126 | 41 | 132 | 13.6 | 4.8 |
| 2 | 0110021720 | 4.02 | 15.06 | 18.27 | 6.74 | 9.95 | 9.54 | 70 | 41 | 81 | 23.7 | 5.4 |
| 3 | 0205061712 | 6.46 | 18.28 | 20.27 | 10.96 | 12.95 | 13.23 | 59 | 40 | 71 | 63.5 | 5 |
| 4 | 0210121959 | 5.96 | 27.93 | 28.14 | 13.59 | 13.8 | 18.11 | 126 | 29 | 129 | 6.9 | 5.6 |
| 5 | 0212050050 | 6.57 | 21.52 | 25.46 | 12.14 | 16.08 | 10.22 | 84 | 40 | 93 | 56.2 | 5.2 |
| 6 | 0212050053 | 6.5 | 20.76 | 21.7 | 11.12 | 12.06 | 10.11 | 80 | 37 | 88 | 131.5 | 4.9 |
| 7 | 0301051851 | 3.21 | 17.67 | 19.07 | 5.72 | 7.12 | 2.99 | 61 | 99 | 116 | 12.7 | 4.4 |
| 8 | 0303030747 | 3.26 | 14.84 | 15.7 | 6.06 | 6.92 | 9.67 | 73 | 41 | 84 | 50.0 | 5.3 |
| 9 | 0310311006 | 5.73 | 24.73 | 34.92 | 11.59 | 21.78 | 26.02 | 117 | 33 | 121 | 20.3 | 6.8 |
| 10 | 0405291247 | 4.32 | 16.69 | 21.18 | 7.36 | 11.85 | 12.52 | 84 | 38 | 93 | 8.0 | 5.9 |
| 11 | 0407051822 | 5 | 16.14 | 20.2 | 8.88 | 12.94 | 17.29 | 54 | 42 | 69 | 7.3 | 4.7 |
| 12 | 0412292259 | 6.92 | 20.35 | 23.83 | 12.74 | 16.22 | 18.01 | 61 | 39 | 72 | 4.0 | 5.5 |
| 13 | 0503300412 | 5.76 | 19.73 | 20.26 | 10.46 | 10.99 | 10.57 | 66 | 61 | 90 | 2.5 | 4.4 |
| 14 | 0508161146 | 7.05 | 17.75 | 23.93 | 9.08 | 15.26 | 16.02 | 70 | 42 | 81 | 250.5 | 7.2 |
| 15 | 0508241915 | - | - | - | 14.77 | 20.86 | 15.17 | 139 | 14 | 139 | 2.0 | 6.3 |
| 16 | 0508310311 | - | - | - | 15.24 | 19.56 | 15.94 | 173 | 22 | 174 | 1.7 | 6.3 |
| 17 | 0509061813 | 6.08 | 17.16 | 17.73 | 11.06 | 11.63 | 13.29 | 36 | 45 | 58 | 7.2 | 4.1 |
| 18 | 0509120428 | 6.85 | 19.87 | 24.54 | 11.91 | 16.58 | 15.22 | 62 | 42 | 75 | 1.7 | 4.7 |
| 19 | 0510121330 | 5.03 | 16.27 | 20.95 | 8.9 | 13.58 | 14.85 | 54 | 43 | 69 | 13.3 | 4.7 |
| 20 | 0510180348 | 5.39 | 16.87 | 19.25 | 9.49 | 11.87 | 13.63 | 55 | 43 | 69 | 12.2 | 4.8 |
| 21 | 0510241835 | 6.53 | 18.26 | 21.28 | 11.04 | 14.06 | 13.23 | 58 | 39 | 70 | 4.0 | 4.8 |
| 22 | 0512022213 | 6.93 | 20.81 | 27.89 | 10.95 | 18.03 | 14.93 | 79 | 40 | 88 | 7.0 | 6.6 |
| 23 | 0512050720 | 7.29 | 23.49 | 26.36 | 10.5 | 13.37 | 14.29 | 112 | 25 | 115 | 2.9 | 5.5 |
| 24 | 0512170332 | 6.87 | 22.79 | 26.61 | 12.53 | 16.35 | 14.13 | 61 | 40 | 73 | 18.6 | 6.1 |
| 25 | 0601182325 | 5.18 | 20.54 | 22.97 | 9.78 | 12.21 | 15.07 | 83 | 36 | 90 | 24.6 | 5.7 |
| 26 | 0602010423 | 7.11 | 20.99 | 26.27 | 12.57 | 17.85 | 14.89 | 71 | 36 | 79 | 2.2 | 4.5 |
| 27 | 0602031303 | 5 | 16.07 | 16.73 | 8.52 | 9.18 | 13.01 | 58 | 42 | 72 | 8.1 | 4.5 |
| 28 | 0604021623 | 5.07 | 15.8 | 16.12 | 9.47 | 9.79 | 9.72 | 37 | 50 | 62 | 7.5 | 4.4 |
| 29 | 0604222336 | 4.18 | 16.43 | 16.94 | 7.57 | 8.08 | 7.51 | 52 | 66 | 84 | 3.1 | 4.6 |
| 30 | 0605062045 | 6.75 | 20.01 | 21.28 | 12.22 | 13.49 | 15.64 | 64 | 38 | 75 | 2.0 | 4.5 |
| 31 | 0607010828 | 6.04 | 18.63 | 21.69 | 11.03 | 14.09 | 12.04 | 60 | 40 | 72 | 11.0 | 5.3 |
| 32 | 0609091936 | 5.31 | 17.86 | 18.65 | 9.49 | 10.28 | 12.24 | 46 | 67 | 81 | 5.5 | 4.9 |
| 33 | 0610020207 | - | 25.62 | 27.01 | 11.98 | 13.37 | 13.36 | 118 | 56 | 131 | 2.1 | 5.2 |
| 34 | 0706131049 | 4.62 | 15.57 | 16.42 | 8.01 | 8.86 | 8.24 | 27 | 66 | 71 | 2.0 | 4.2 |
| 35 | 9605231836 | 6.51 | 20.18 | 21.43 | 11.51 | 12.76 | 11.25 | 80 | 39 | 89 | 448.3 | 5 |
| 36 | 9712071250 | 2.92 | 15.67 | 17.25 | 4.78 | 6.36 | 8.78 | 69 | 83 | 108 | 111.4 | 5.2 |
| 37 | 9805210654 | 4.78 | 18.25 | 18.74 | 8.21 | 8.7 | 11.65 | 57 | 84 | 101 | 112.6 | 5 |
| 38 | 9911151035 | 7.1 | 21.62 | 24.67 | 11.98 | 15.03 | 14.68 | 81 | 49 | 95 | 88.5 | 5.5 |
| | average | 5.7 | 19.1 | 21.8 | 10.2 | 13.1 | 13.2 | 75.3 | 45.5 | 91.1 | 40.8 | 5.2 |
| | std | 1.2 | 3.1 | 4.2 | 2.4 | 3.7 | 3.8 | 30.5 | 16.9 | 25.3 | 84.4 | 0.7 |
| | max | 7.3 | 27.9 | 34.9 | 15.2 | 21.8 | 26.0 | 172.7 | 99.0 | 174.0 | 448.3 | 7.2 |
| | min | 2.9 | 14.8 | 15.7 | 4.8 | 6.4 | 3.0 | 27.5 | 14.0 | 57.7 | 1.7 | 4.1 |

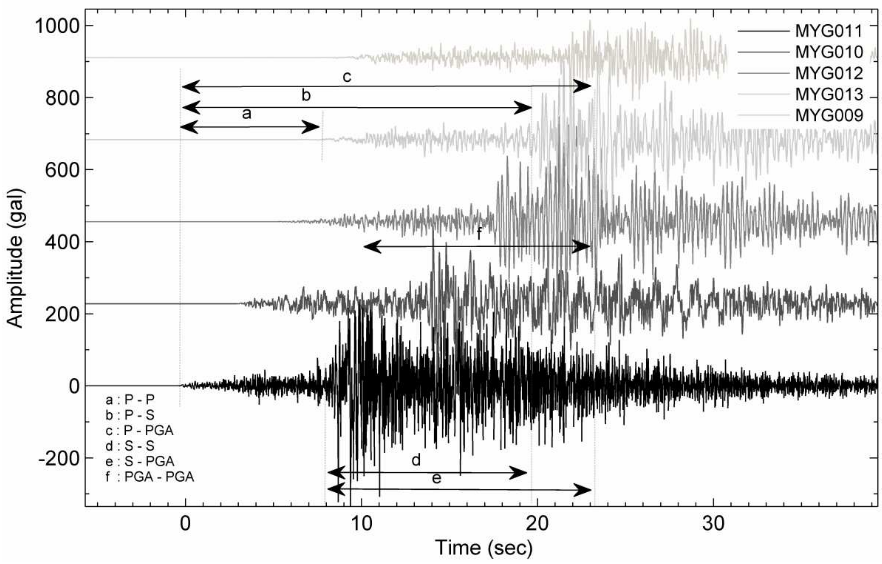



Figure 6 Recorded waveforms at five stations in Miyagi prefecture (August 16, 2005)

In general, accuracy of the hazard prediction increases with time, while the warning time available decreases. Therefore it is necessitated to calculate the probability of available time in region where a destructivity earthquake is most likely happens. Here the authors assessed the distribution of warning times for many likely earthquakes in northeastern earthquakes of Japan.

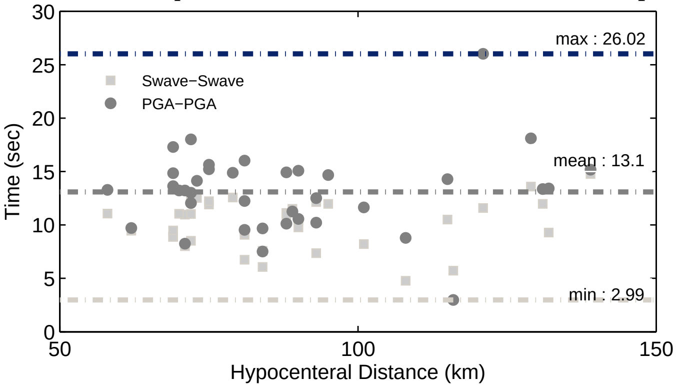
The expressions; “Alert time”, “Warning time”, “Available time” are all used for variety of authors in different meanings but the same intentions. Another difference of the studies until now is the considerations about occurrence of S wave or peak ground motion. Therefore it is important to evaluate each in itself. In this part of study, onset of P-wave in Oshika is defined as the “alert time”, the warning time is then the difference between the alert time and the estimated time of S wave or peak ground shaking for a given location. Warning times are calculated for a total of 38 earthquake epicenters. The all epicenters locate offshore, the faults identified as those most likely to cause damaging earthquakes in northeastern Japan. The total probability of occurrence within 10 years was estimated for Miyagi oki at 60%. Within the region that the fault is most likely to rupture is Miyagi fault with the probabilities of producing a magnitude 7.3 or greater earthquake of 50%.

The warning time in a given earthquake is dependent on the hypocentral location where the rupture initiates. Nearer the record to the epicenter, the wave encompasses the P and S phases. For the two locations in the prefecture onset of P and S wave are picked by manually. Therefore there is no assumption for epicenter location. We directly survey the offline study with recorded waveforms.

The alert time is dependent on the relative locations of seismic stations to detect the P-wave arrivals. The alert time for each earthquake is accepted as the time at which 0.2 seconds of P-wave data are available at the nearest inland point, Oshika and processing delay of 0.4 sec. A 0.4 sec delay accounts for transmission of waveform data from Oshika to network operation center, processing time. Current seismic infrastructure in Sendai with the development of our regional warning system, the most significant delay, packetization of data before transmission from each station is solved with the variable packet settings. The current setting is set to 0.2 sec delay for packetization. The transmission of data to the processing center is less than 0.2 second depends on our measurements. The processing time for the data is negligible. Our estimates describe what is possible using the existing seismic network hardware. The time could also be improved through more advanced network with undersea processing stations.

In Figure 6, the illustration of different time intervals is shown. The intervals all a, b, c, d, e, f indicates that the first expression is the Oshika and the second is the far site records. The same calculations made by for the four major cities, Sendai, Ishinomaki, Shiogama, Taiwa. This calculation is specifically for the K-net stations, but it does not vary significantly over the vicinity of the cities. In the same figure it can be derived that even for the location itself, it is possible to warn the residents after detection of P-wave in the same location.

On the other hand, we investigated not just P-wave and S wave difference but S to S wave and PGA to PGA difference for the same location. These indicators are in fact very important when the accuracy is considered to be very essential. In Figure **7**, the circles indicate PGA-PGA where squares indicate S-S wave difference. The mean value time difference of PGA to PGA in both site is 13.1 second with about 10 second standard deviation. This average is indicating that before the PGA of the destructive ground motion reaches the Sendai, there is 13.1 second average not just detection of P-wave but also after detection of the peak ground motion in Oshika. Even for the minimum 2.99 sec is a significant because one of the biggest super conductor company in the area released a news that they can able to stop their produce lines in 3 seconds and it is tested 2008 Iwate-Miyagi inland earthquake which occurred in south of Iwate prefecture.



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