AN AUTOMATIC PROCESSING SYSTEM OF HI-NET WAVE FROM DATA FOR THE EARTHQUAKE ALARM INFORMATION

SHIGEKI HORIUCHI, HIROAKI NEGISHI, AYA KAMIMURA,
TAKAKI IWATA AND SHUNROKU YAMAMOTO
National Research Institute for Earth Science and Disaster Prevention,
Tsukuba, Japan

ABSTRACT

The most of earthquake hazard is brought at times after arrivals of the S wave, whose amplitude is about five times larger than the P wave. We developed an earthquake alarm system, which can determine hypocenter parameters very quickly and transmits the earthquake information before S wave arrival, so as to create an opportunity to decrease the speed of trains, to cut current for some factories, to stop gas supply etc, before hitting of large amplitude earthquake shakings. Since earthquake alarm system asks us to determine earthquake parameters as first as possible, we cannot wait till waveform data from a sufficient number of stations are collected. Considering that all stations observe P wave arrivals in a case of a large earthquake occurrence, we developed a novel method determining precise hypocenter locations for a large earthquake by using arrival times for a few stations and time data for many stations that P wave have not yet arrived. The usage of not yet arrived data makes possible not only to determine precise hypocenter parameters within a few seconds but also to distinguish extraneous arrival time readings and remove them automatically. It was shown from the application of the present method to seismic waveform data for about one hundred earthquakes that almost all events except ones far from the network can be located precisely within a few seconds, when the most of seismic energy does not arrived even to the closest station. We started recently to broadcast earthquake information immediately and widely by using a satellite transmitting system.

1. INTRODUCTION

A large earthquake produces strong ground motions at its epicenter area. If we developed an earthquake alarm system, which can determine precise hypocentral parameters within a few seconds by using P wave data and transmit earthquake alarm information before the arrival of the large amplitude S wave, it is possible to mitigate seismic hazard by decreasing the speed of trains, cutting current for some factories, stopping gas supply etc.

Earthquake alarm system requires the development of a very good and reliable automatic processing system of seismic waves. Previous studies (Yokota et al., 1981 ; Horiuchi et al., 1992; Cansi, 1995; Kanamori, 1993;

Ellsworth and Heaton, 1994; Kanamori et al., 1997) developed automatic processing systems, which detect earthquakes, determine hypocenters, magnitudes and focal mechanisms automatically by picking P and S wave arrival times and measuring their amplitudes.

There are very large differences between real-time systems mentioned above and the automatic processing system for the earthquake alarm broadcasting. The former can use almost all available data, but the latter must analyse when only a few second P wave data of a few stations are available. In general, these real time systems miss-locate or fail to locate 10 to 20% of events, even though they use all available data. However, it is not very serious for them because they have time to correct calculated results manually. The alarm system is designed so as to control many kinds of machines, trains, buildings, etc and to do something to save life before hitting of strong ground motions. False alarms cost huge amounts because they cause disruptive and unnecessary stoppages in transport, industry, business and nearly every other sector in society. The development of the alarm system requires the solution of technical difficulties of how to determine earthquake parameters very quickly but without estimation errors.

In Japan, an alarm system, UreDAS (Nakamura, 1988, 1996) was developed and it is already in use in railroad alarm systems, which stop trains at the time of the occurrence of a large earthquake. It determines all hypocenter parameters by using only one station data. Therefore, there is a considerable amount of estimation error of hypocenter location owing to the difficulty of estimating epicentral distance from only the P wave data of a single station.

In the present study, we developed a novel method to determine precise hypocenters of large events within a few seconds by using real-time data of seismic networks of Hi-net and Kanto-Tokai, which installed very high space density and high dynamic range seismic stations covering whole Japan Islands. The new method uses not only P wave arrival times but also time data for many stations at which the P wave has not yet arrived.

2. METHOD OF HYPOCENTER LOCATION

We developed a novel method to determining hypocenters very quickly but without a large estimation error. When a large earthquake occurs, people in the focal area feel the ground shaking and all seismometers detect P wave arrivals so long as they are working correctly. Consider that a large earthquake occurs at a point and two stations detect P wave arrivals up to a moment, T^{now}, but the other stations have not detected. P wave arrival times for the two stations restrict the permissible hypocenter location somewhere on a curved surface, as can be seen in Fig. 1. However, we cannot say where it is on the curved surface.

Since we assume this earthquake to be large, all stations will detect seismic signals later so long as they are working correctly. We can consider in this case that this event occurs at an area and at a time where all stations except the two cannot detect P wave up to this moment. Therefore, we have inequality equations for all stations except the two that theoretical arrival times for them must be larger than this moment.

$$T^{now} - T_{hi}(\phi, \ \lambda, \ h) - T > 0 \qquad (1)$$

where, T_{hi}, T, ϕ, λ and h are P wave theoretical travel time to i-th station, origin time, latitude, longitude and focal depth of the event. We call T^{now} in Eq.(1) P wave not yet arrived data (NYAD). As clearly shown in Fig.1, NYAD give us very important information about the permissible hypocenter location.

Next, we show the method how to use NYAD for locating hypocenters numerically. We define residuals for both P wave arrival times and NYAD. Residuals for arrival time data can be put by

$$R_{pj} = T^{p}_{j} - T_{hj}(\phi, \ \lambda, \ h) - T \qquad (2)$$

where, T^{p}_{j} is P wave arrival time for j-th station.

We define travel time residuals for NYAD as follows.

$$R_{ni} = T^{now} - T_{hi}(\phi, \ \lambda, \ h) - T \qquad (3)$$

if $T^{now} - T_{hi} - T < -\varepsilon_O$

$$= -\varepsilon(\Delta, h) \qquad (4)$$

if $T^{now} - T_{hi} - T \geqq -\varepsilon_O$

where, ε_O is a some positive small constant. $\varepsilon(\Delta, h)$ is an arbitrary function having very small value. Equation (3) becomes large if Eq. (1) is not satisfied and small if satisfied.

The hypocenter location is determined so that the sum of squares of residuals becomes minimum as,

$$\rho^2 = \Sigma w_{pj} R_{pj}^2 + \Sigma w_{ni} R_{ni}^2 \qquad (5)$$

where, w_{pj} and w_{ni} are weights for P wave arrival times and NYAD. We used a numerical method to determine hypocenter parameters, which makes Eq. (5) minimum.

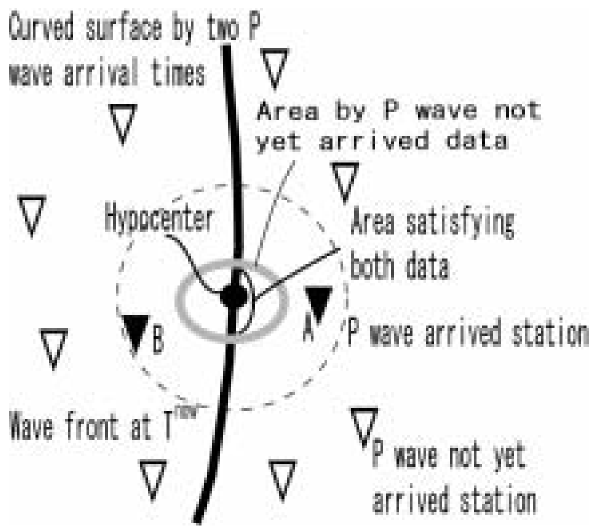

Fig.1: Schematic map showing the advantageous of using P waves have not yet arrived data (NYAD).

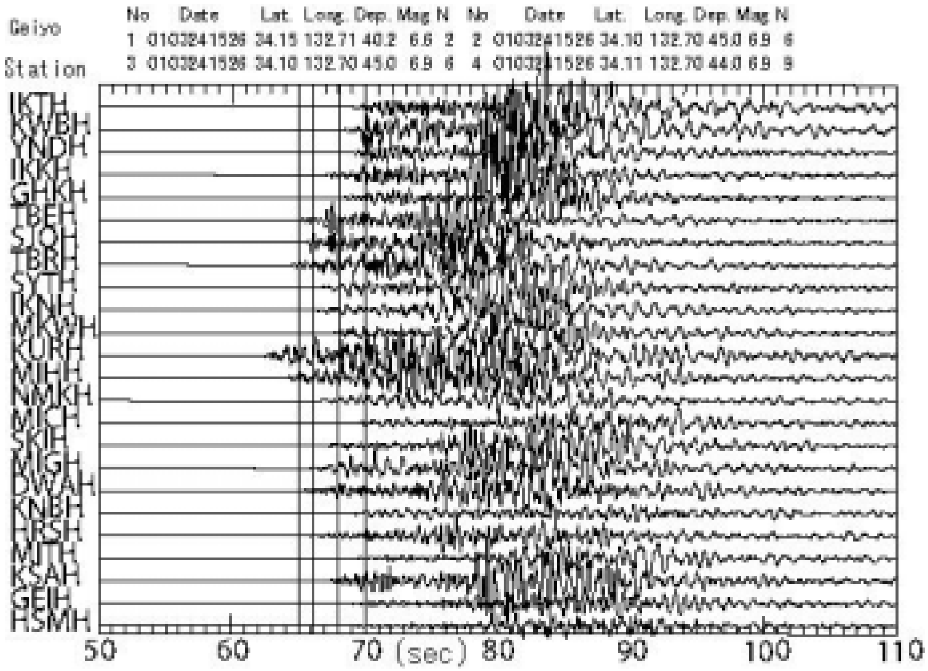

Fig. 2: Plots of seismograms for the Geiyo Earthquake (M7.0) together with hypocenter parameters obtained by the present system. Hypocenter parameters are calculated four times and the four vertical solid lines show moments when they are obtained.

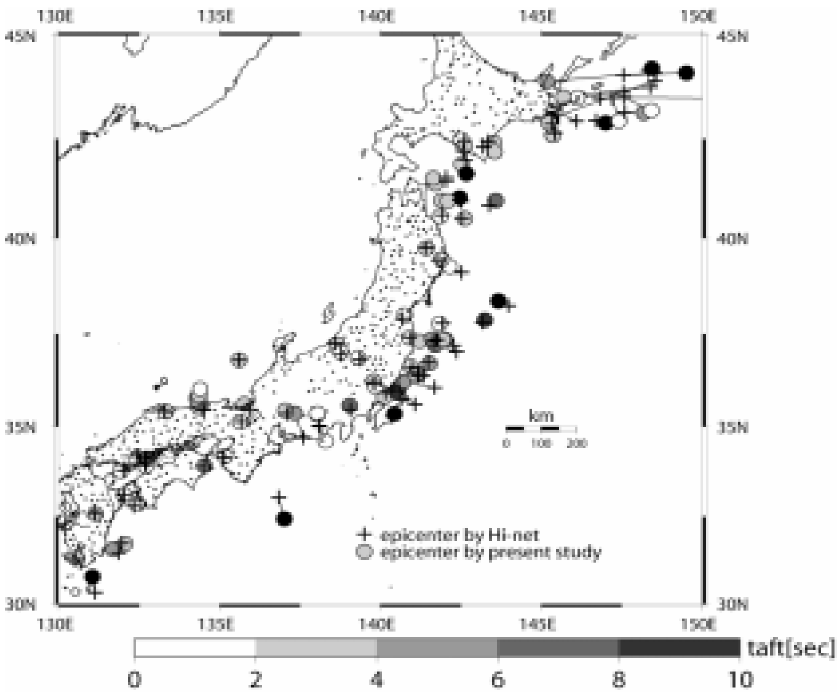

Fig. 3: Comparison of epicenters determined by the present system with those by manually picked data. Gray scale shows times of hypocenter location measured from the arrival of P wave to the closest station. Almost all events are located within a few seconds. The events shown by black colour are small events and are triggered by S wave arrivals.

When a large earthquake is detected, P wave arrival times for triggered stations are measured automatically by using the similar manner to Horiuchi et al. (1999), who use Akaike Information Criterion (Akaike, 1973). Since there are cases that amplitude of the initial part of P wave is small, we search P wave arrivals not only for triggered stations but also for their neighbour stations. We take a long time window of about 40 sec before the trigger time for P wave picking so as to measure correct P wave arrival times even for stations, which are triggered by the arrival of S wave. Since we use NYAD for the hypocenter location, it is very important to check carefully if small amplitude P waves have already arrived or not.

Earthquake magnitudes are estimated from seismic moments obtained from one Hz velocity seismograms (Negishi et al., 2002). Earthquake shaking intensity at a city is calculated from the obtained hypocenter location and magnitude by using an empirical equation (Midorikawa, 1993) .

3. REAL-TIME EARTHQUAKE INFORMATION SYSTEM (REIS)

We developed a real-time earthquake information system (REIS) by using waveform data of two seismic networks, Hi-net and Kanto-Tokai, operated by National Research Institute for Disaster Prevention and Earth Science (NIED). Both networks set three component velocity seismometers in a borehole deeper than 100m. Hi-net is a very highly sensitive and high space density seismic network set up after the Kobe Earthquake in 1995 in whole Japan Islands with a station spacing of 20 to 25 km. A/D converter of 24-bit accuracy is installed and the total number of stations is approximately 720. Kanto-Tokai net was set up in the Kanto-Tokai District in the beginning of 1980 decade. The accuracy of A/D converter is 12-bit and 8-bit compressed data are sent. It has about 60 stations. Seismic waveform data for both network are sent to NIED by using telephone-linked telemetry. Recently, Hi-net installed about 60 high quality seismic stations at Kanto-Tokai District, though these data were not yet used.

We use two LINAX computers. One determines earthquake parameters and the other sends them to users outside. We divide the software determining earthquake parameters into two. The first one reads waveform data of Win format, un-compresses them, and writes un-compressed data on the sheared memory, which has the capacity to store all waveform data for six minutes. The other reads waveform data from the sheared memory, detects seismic events, picks P wave arrivals, determine hypocenters and moment magnitudes, and sends them to the second computer.

The detection of a large earthquake occurrence is made when more than two stations observe acceleration larger than a threshold level. However, there are cases that two stations located far away observe large amplitude noises simultaneously, since we use a large number of stations covering whole Japan Islands. Event detections are made only when a station detects trigger event and more than one stations among 20 stations of its neighbour also detect a large amplitude signals.

When a large earthquake occurs, the number of stations observing it increases with time. More data make it possible to determine more accurate earthquake parameters. We check the number of stations detecting P waves every one-second and re-calculate earthquake parameters at moments when the number is increased. It takes only about 0.1 second for the UNIX computer to determine earthquake parameters, while it does all the jobs of picking P wave arrivals for triggered stations, searching for P wave arrivals of about 100 stations located near triggered stations, calculating a converged hypocenter solution by the use of a grid search method, and estimating moment magnitude.

We checked the software determining earthquake parameters by using waveform data of about 100 large earthquakes larger than M4.5, which occurred in the last two years. Instead of running the first software, which reads real-time Win format data and write un-compressed data on the sheared memory, we run a program that reads waveform data from the hard disk and write them on the shared memory with the same speed as they were observed. We use only Hi-net data for checking software.

Geiyo Earthquake with magnitude 7.0 occurred on March, 24, 2001 beneath the western part of the Inland Sea of Japan, Chugoku District. This earthquake occurs in the sinking slab of Philippine Sea plate and the focal depth by JMA is 45 km. We show the computed result in Fig.2. The first solution is obtained three second later from the P wave arrival to the closest station. Calculated magnitude for the first is 6.6 and it becomes 6.9 in the second to fourth solutions. Although the first solution is determined by arrival times of two stations, it is accurately determined. Difference in focal depths is only 5km.

Figure 3 shows comparison of epicenters located by REIS and those determined by the use of manually picked data. Differences of hypocenter locations between the two are small except for events occurring in the northeast of the seismic network. Hypocenter location errors are estimated to be a few to a several km in the seismic network. They become larger in offshore areas. Since the azimuthally coverage of stations in the area northeast of the network is very poor, NYAD do not make the area of the permissible hypocenter location small. Hypocenter location errors for some

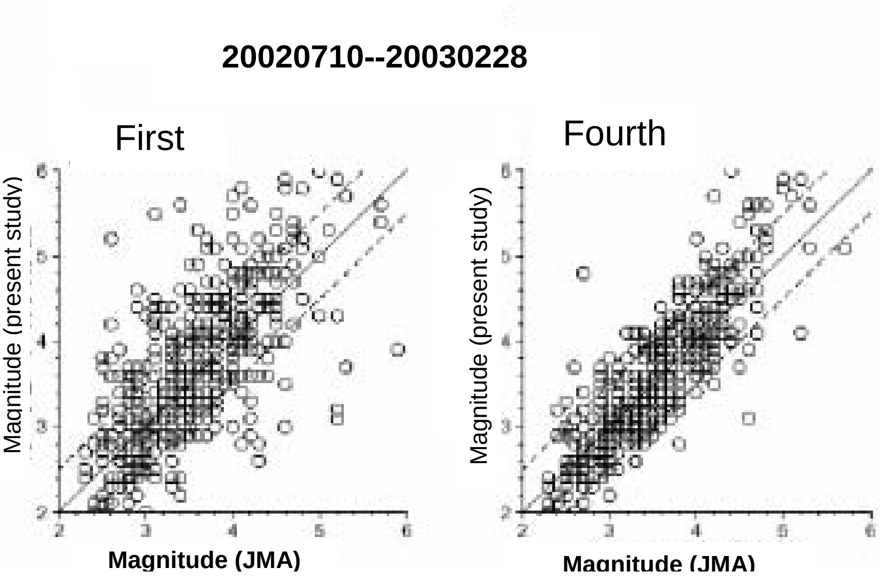

Fig. 4: Comparison of magnitudes determined by the present system and those by Japan Metrological Agency(JMA).

Events have location errors larger than 100 km. Gray scale shows times when earthquake parameters are determined after P wave arrivals to the closest stations. Most of events are determined within 4 seconds. There are events with blue colour. They are small events and are triggered by S wave. It is important to notice that our system can locate precise hypocenters even for events triggered by S waves.

Figure 4 shows comparisons of magnitude determined by REIS and those by JMA. We started real-time processing from July, 2002 and this is the result of real-time processing. The left and right show magnitudes determined in the first and fourth iterations, respectively. It is shown that magnitudes for about 70% and 90% of events are determined within errors of 0.5 in the solutions of first and the forth iterations, respectively.

4. DISCUSSION AND CONCLUSION

We develop a real-time earthquake information system (REIS), which determines earthquake parameters within a few seconds from the arrival of P wave to the closest station and sends earthquake alarm information. We introduced a novel method of hypocenter locations by using not only P wave arrival times but also time data for many stations that P waves have not yet arrived (NYAD).

Earthquake parameters for about 5 hundreds felt earthquakes were obtained by the real-time operation of REIS for eight months from July 2002 (Horiuchi et al., 2003). There are about 3 % of felt earthquakes, whose hypocenters are not determined or un-correctly determined. REIS cannot process correctly for events accompanying another events simultaneously. There are a small number of large events, especially occurring beneath the Pacific Ocean, whose P wave amplitudes are too small to be measured automatically. Although, most of them are not located, there are a small number of events, which are un-correctly processed. It is very important to continue to improve the software of picking and locating hypocenters.

Recently, we started an experimental service of broadcasting real-time earthquake information immediately after getting earthquake parameters by using a satellite system developed by Urabe and Tsukada (1992), which collects waveform data of almost all seismic stations in Japan and broadcast them. We think that the present system is very effective to mitigate earthquake hazard. It is noticed that we are willing to distribute our software together with the manual showing how to use it.

ACKNOWLEDGMENTS

We are grateful to Drs. Y., Hayashi, Nagoya University, Drs T. Matsumoto, T. Kunugi, and S. Miura, NIED and other staffs of NIED for their valuable discussions.

REFERENCES

Akaike, H. (1973). Information theory and an extension of the maximum likelihood principal, 2nd International Symposium of Information

Theory, eds, B.N.Petrov and F. Csaki, 267-281, Akademia Kiado,Budapest.
Cansi, Y.(1995). An automatic seismic event processing for detecting and location:The P.M.C.C. method, Geophys. Res. Lett., 22, 1021-1024.
Ellsworth, W. & Heaton, H. (1994). Real-time analysys of earthquakes and rapid damage assessment. Sensors(April) 27-33.
Hasegawa, A. ,D. Zhao, S. Hori., A. Yamamoto, and S, Horiuchi,(1991). Deep structure of the northeastern Japan arc and its relationship to seismic and volcanic activity, Nature, 352, 683-689.
Horiuchi, S. T. Matsuzawa and A.Hasegawa (1992). A real-time processing system of seismic wave using personal computers, J. Phys.Earth, 40, 395-406.
Horiuchi, S. T. Matsuzawa and A.Hasegawa (1999). Automatic data processing system of seismic waves that works even at times of huge seismic activity, J. Seismol. Soc. Jpn, 52, 241-254.
Horiuchi, S., H. Negishi, K. Abe, A. Kamimura(2003), Real-Time Earthquake Information System, in preparation.
Kanamori, H. (1993). Locating Earthquakes with Amplitude: Application to Real- Time Seismology, Bull. Seismol. Soc. Am., 83, 264-268.
Kanamori, H., E. Hauksson, and T. Heaton (1997). Real-time seismology and earthquake hazard mitigation, Nature 390, 461-464.
Midorikawa, S. (1993). Preliminary analysis for attenuation of peak ground velocity on stiff site, Proc. of the International Workshop on Strong Motion Data, Vol. 2, Port and Harbor Research Institute, Japan, and U. S. Geological Survey, U. S. A., 39-48.
Nakamura, Y. (1988). On the Urgent Earthquake Detection and Alarm System(UrEDAS). In Proc. 9th World Conf., Earthquake Eng. VII, 673-678 (Jpn Assoc. for Earthquake Disaster Prevention, Tokyo, Kyoto)
Nakamura, Y (1996). Real-time information systems for hazards mitigation. In Proc. 11th World Conf. Earthquake Eng. CD-ROM, Pap. No.. 2134 (Pergamon, Oxford).
Negishi, H., S. Horiuchi and K.Abe, Development of REIS (Real-Time Eartquake Information System) –Determination of magnitude-, Program and Abstracts,The Seismological Soc. Jpn. 2002, Fall Meeting, C04, 2002.
Urabe and Tsukada(1992). Programme and Abstracts, Seism. Soc. Jpn, No.2, 107.
Yokota, T., S. Zhou, M. Mizoue and I. Nakamura (1981). An automatic measurement of arrival time of seismic waves and its application to an on-line processing system, Bull. Earthq. Res., Inst., 55, 449-484.
Zhao, D., S. Horiuchi, and A. Hasegawa (1990). 3-D seismic velocity structure of the crust and uppermost mantle in the northeastern Japan arc, techtonophysics, 181, 135-149.
Zhao, D., A. Hasegawa, and S. Horiuchi (1992). Tomographic imaging of P and S wave velocity structure beneath northeastern Japan, J. Geophys. Res., 97, 19,909-19,928.