Early Warning Systems

By

Katsuhisa Kanda
Hiroaki Yamanaka
Masamitsu Miyanura
Yoshiki Ikeda
Takafumi Moroi

Donald Helmerberger
Hiroo Kanamori

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California Universities for Research in Earthquake Engineering (CUREe)

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Early Warning Systems

Don Helmberger and Hiroo Kanamori
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INTRODUCTION

The recent advance in real-time seismic data acquisition is making it possible to estimate earthquake characteristics while the event is still in progress. This source information coupled with stored strong motion responses for characteristic earthquakes allows the capability of predicting the level of strong motions before the most damaging shaking arrives. Essentially, the faster traveling P-waves and the beginning portion of S-waves near the epicenter provides sufficient information to determine the nature of the event. This allows a few seconds of warning time depending on the epicentral distance. For example, we could expect about 10 to 15 seconds of warning time in Los Angeles for a San Andreas type of event and similarly in the Tokyo situation. This provides adequate time for some emergency operations such as back-up electrical power turn-on, shut-down of natural gas, etc., see a recent Stanford report (Takeuchi et al., 1992). Moreover, an accurate picture of ground shaking levels in the damaged region after the motions arrive can be assembled rapidly to assist in emergency operations.

In this report, we present work developing this concept of early warning. In the first part, we examine the feasibility of finding earthquake location, depth, source mechanism and source-time function with broadband data from a single station of a few stations. We also consider the problem of using this information to predict strong motions in a region with large variations in crustal structure. These results suggest that the physical problem can be addressed with some basis. In the second part, we consider some preliminary modeling of data recorded for a small event by the TKO broadband array. A one-dimensional model was constructed which roughly fits the waveforms from this event. Variations in the data from different stations suggest that shallow variations in the crust need to be modelled. In the third part, we consider the problem of discriminating deep earthquakes from shallow earthquakes. Depth determination is an area where the current Kajima early warning program has had difficulties, as discussed at the workshop. We suggest adding the Pnl waves and surface waves into the regression equation for depth.
PART 1 - FEASIBILITY

The prospects for accurate prediction of earthquakes remain as poor now as they have throughout this century. Other areas of study in seismology, however, have experienced significant advances that can be put to use for seismic hazard abatement in urban areas. Broadband digital instruments record high quality waveforms for both strong and weak motions. Because these stations can record smaller, more numerous events as well as large, hazardous events, a catalog of Greens functions can be developed for an area and used to find source characteristics for large events. The records of the small events can be used either directly as empirical Greens functions or as a basis for crustal models to calculate synthetic Greens functions. The advantage of theoretically derived Greens functions is that they can be calculated for any range and depth. They can also be stored as the response for three fundamental faults. These responses can be combined to produce the three component response for an arbitrary point source by a weighted sum determined by the strike, rake and dip. With the catalog of Greens functions, rapid inversions for a source parameters can be done (Dreger and Helmberger, 1993; Zhao and Helmberger, 1994). These inversion techniques work well for sparse networks of broadband data. Many times, data from even a single station is sufficient to find an approximate solution.

This raises the possibility that data from a single near-field broadband receiver would be enough to determine source parameters and predict ground motions throughout the region. Using this strategy, we could predict ground motions in areas, like the Los Angeles basin, where seismic energy is focused and heavy damage is possible. How these predicted ground motions could be used depends on where the event occurred. If the earthquake occurs within an urban area, the calculated ground motions could be useful for rapid assessment of areas of greatest damage. If the earthquake occurs outside an urban area, the ground motions for the urban zone can be calculated before the energy propagates into the area. In this case, the calculations serve as a prediction of imminent ground motions and warnings could be posted to organizations for emergency machinery shutdown or other response.
Many cities have been built in the vicinity of faults capable of producing damaging earthquakes. For this reason, the scheme presented here for early warning and ground motion prediction could be widely applied. In this paper, we begin testing the credibility of the strategy discussed above. We give an example of using data from a single broadband station to invert for the source parameters of strike, rake and dip. These parameters are used to calculate ground motions for the locations of other receivers and the calculations are compared with the data from these sites. The source inversion is repeated with increasing amounts of data to show how the source mechanism found in the inversion improves and stabilizes with additional data.

**Outline of Proposed Method**

When an earthquake occurs, it must be recognized and located by the closest station. Procedures to pick an event with a single station and determine the back azimuth from the first motion amplitudes of the three components have been developed by Magotra et al. (1987) and Nakamura (1988). We have developed a computer program to implement a single-station determination of earthquake source parameters. Details of this method, with some test results are presented in Appendix A. The distance from source to receiver is not known until the S wave arrives, but it would be preferable to start the source inversion as early as possible. At a given moment, after the P wave and before the S wave, the duration of the Pnl constrains a minimum possible distance because we know that if the distance were shorter than this minimum the S wave would have already arrived. As a result, the inversion can be started with this constraint. As more Pnl record arrives at the stations, the minimum possible range is increased. Finally, the S wave arrives and the distance for the single station inversion can fixed. With the location of the event determined, the distance and back azimuth from the source to other stations in the network can be calculated. As these stations begin recording the event, the data can be included in the inversion process. The source inversion is repeated with increasing amounts of data. After each inversion, ground motion predictions are calculated with the source parameters for sites throughout the region.
The inversion technique used in this paper does a grid search over the source mechanism parameter space while allowing different segments of the waveform to shift in time independently (Zhao and Helmberger, 1994). The Greens functions were calculated from a standard southern California velocity model (Table 1). The error of the synthetic waveform relative to the data is found for each set of possible source parameters. The grid search is first done with a coarse mesh to roughly determine the global minimum in the error. A search over a finer grid centered on the coarse mesh minimum is done to refine the solution. The general scheme for early warning can be implemented with other inversion techniques. Advantages of the technique of Zhao and Helmberger are that it can work with broadband data, that it can work with arbitrary portions of the data, and that it allows portions of data to shift relative to each other during the inversion. The flexibility with which this technique handles portions of data makes it relatively insensitive to flaws in the crustal model used to calculate Greens functions.

RESULTS FOR SIERRA MADRE

Figure 1 is a map of southern California with the location of the June 28 1991 Sierra Madre (M = 5.8) mainshock and the TERRAscope stations used in this study. The source mechanism shown was found by Dreger and Helmberger (1991) with the complete waveforms from these stations and refined Green functions. Table 2 lists the locations of the mainshock hypocenter and the TERRAscope stations. In southern California, real time warning in urban Los Angeles of a large event on the San Andreas fault would be helpful. In this paper we use the Sierra Madre mainshock as a reciprocal example. It occurred near Los Angeles and was recorded near the San Andreas fault.

Figure 2 shows how the estimate of the source mechanism and magnitude of the Sierra Madre mainshock changes with time after the source rupture. The four mechanisms correspond to inversions with the data available at that time after the event. The size of the mechanism diagram is proportional to the seismic moment, \( M_0 \). The source mechanism found with the complete TERRAscope records from PAS, SVD, GSC, ISA, and PFO (Dreger and Helmberger, 1991) is shown in the upper right corner of the figure. The inversions were done using Greens
functions calculated from a standard southern California crustal model (Table 1). The Greens functions were calculated for a source of depth 11 km with a triangular source time function lasting 1 second. The first inversion solution, based only on the PAS Pnl waveforms, is predominately strike-slip and requires a seismic moment that is 2 to 3 times too large. The second inversion solution is based on the Pasadena Pnl and surface wave data. It does a much better job of matching the complete solution. It is a predominately thrust mechanism with a moment of $3.4 \times 10^{24}$ dyne-cm.

The remaining two mechanisms in Figure 2 indicate how the solution fluctuates with the addition of data from stations SVD and GSC, ISA and PFO. The additional data gradually brings the source parameters into agreement with the complete solution. The moment fluctuates by about 20%.

Figures 3 to 6 display the evolution of the fit of the synthetic waveforms to data. In these figures the data waveforms for SVD, GSC, ISA and PFO are offset behind those of PAS by the appropriate relative travel time. This indicates the time it took the wavefronts to propagate to these stations after the Sierra Madre mainshock rupture. The boxes in each figure enclose the data that was used for that inversion. The Greens functions used for station PAS in the inversion are calculated for a range of 30 km. The actual distance from the Sierra Madre epicenter to the Pasadena station is 20.6 km. The use of the 30 km Greens functions shows what happens when the range is not accurately known (see discussion above).

Figure 3 shows data and synthetic waveforms for an inversion using only the PAS Pnl waveforms. The Pnl segment is so short that only the overall slope of the waveform controls the inversion. This is not very robust. The predicted waveforms for the unused portions of the data, calculated using this mechanism, are poor fits to the data. The radial and vertical shear waves at Pasadena are fit reasonable well, but the tangential component has the wrong polarity. The waveform fits at the other stations follow a similar pattern. The Pnl portions of the synthetic waveforms match the first-motion polarity at SVD and PFO, but not at GSC and ISA. The shape
of the Pnl waveforms is not very well matched at any of these stations. The tangential waveforms appear to have the wrong polarity at all the stations.

Figure 4 shows the data and synthetic waveforms for an inversion using the entire PAS waveform. The polarity of the tangential component of the synthetic is corrected in this inversion, and the fit of the shear waves on all three components brings the seismic moment down by a factor of 2. This improves the fit of data and synthetics at the other stations.

Figures 5 and 6 show the inversion results when the SVD Pnl data and the whole SVD record and GSC, ISA, PFO Pnl data is included, respectively. The additional data does not have an obvious effect on the synthetic waveforms, but it does rotate the strike and rake of the source into closer correspondence with the complete solution of Dreger and Helmburger (1991).

Figure 7 is a plot of the error of the synthetic waveforms for each inversion. The black circles are the error of synthetic waveforms relative to the data used in the inversion (the boxed data in the previous figures). The error is lower when there is less data because the solution is less constrained. The white circles are the error of the synthetics relative to all the data. The error relative to all the data rapidly approaches the error relative to the inverted data. This indicates that the single station solution with data from PAS predicts the ground motions for southern California almost as well as the solution based on the complete data set.

DISCUSSION

The inversion results shown here are based on Greens functions calculated with an averaged model of the southern California crust. This works well when there is data from more than one station, but the inversion for data from just one local station would be better if the Greens functions were refined for that particular area. This can be done with small events or a previous moderate event in the area. For the path from the Sierra Madre mainshock to PAS, for example, Dreger and Helmburger (1991) used Greens functions calculated for a model based on the 1988 Upland earthquake sequence to the east (Dreger and Helmburger, 1990).

Another refinement would be incorporating the effects of local receiver structure in ground motion predictions. The effect on waveforms of lateral heterogeneities in the crust can be
significant. As an example, the change in the response due to the Los Angeles basin is dramatic when records are compared from the PAS and USC TERRAscope stations. Weak motions can be used to develop transfer functions needed to map hard rock response, such as at PAS or RPV, into the basin response, such as at USC. Incorporating local receiver structure would be based on a catalog of either with theoretical Greens functions calculated from a velocity model of the receiver structure or empirical Greens functions. Empirical Greens functions would be recordings of small events on the perimeter of the receiver structure. Theoretical Greens functions are more flexible than empirical Greens functions because they can incorporate arbitrary source parameters. If the receiver structure is complex, however, it may be difficult to model it completely. Creating a catalog of empirical Greens functions is most feasible in areas with a dense network of broadband stations.

Figure 8 shows the convolution of a theoretical two dimensional basin response with a record from station PAS. It is compared with the record at the USC station in the city of Los Angeles. The basin response was generated by modeling the \( M = 5.3 \) aftershock of the 1987 Whittier Narrows sequence just east of Los Angeles (Scrivner and Helmberger, 1994). The earthquake that this response is convolved with is a \( M = 4.2 \) event that occurred on 21 August 1993 on the San Andreas fault near Palm Springs. The convolved waveform compares well with the USC data for about 15 seconds after the S wave, but it does not match the long duration of the USC data. When data and theoretical functions are convolved together some empirical factor has to be included to correct the amplitude the output waveform. This factor could be determined by applying the convolution technique to a set of events along a similar azimuth from the location with complicated site conditions. An entirely theoretical approach avoids this complication of patching data and synthetic waveforms together. Figure 9 shows synthetic waveforms calculated with two different numerical techniques for a two-dimensional cross-section. Figure 9a shows waveforms calculated by a finite difference technique. For long cross-sections, this calculation technique is slow and expensive. Figure 9b shows waveforms calculated by a combination of generalized-ray and finite-difference techniques. The generalized-
ray technique is calculates the response for the one-dimensional part of the model quickly and inexpensively. The finite-difference calculation only has to be performed for a portion of the model. The waveforms in Figures 9a and 9b are essentially identical. This hybrid calculation reduces the cost of developing a library of theoretical Greens functions for two-dimensional models. In Figure 10 the combined generalized-ray finite-difference technique is used to calculate synthetic waveforms for a two-dimensional appropriate for the path from Palm Springs to USC. The panel on the left shows a comparison of the synthetic waveform with the data at USC. The panel on the right compares the arrival of seismic energy at USC as a function of time. For about 20 seconds after the arrival of the shear waves, the synthetics match the data well in energy content and waveform characteristics. The extended coda in the USC data is due to very shallow structure. Introducing small, shallow “micro-basins” into the model at the surface directly under the receiver is an effective way to match the data.

In the results shown here the depth and source time functions are fixed for all inversions. The inversion does not solve for these parameters, but repeated inversions can be done for different depths and source time functions to find the best fit. With improved Greens functions around the closest station, the depth estimate of the event can be improved.

A number of real-time broadband systems are presently being installed in urban regions around the world. These stations are capable of recording both strong and weak motions. Since weak motions are quite common, a catalog of Greens functions (empirical and theoretical) can be built for the region. This would include developing transfer functions needed to map hard rock response to nearby soft soil or basin sites. Using the Los Angeles area as an example, the strategy discussed in this paper suggests that it is possible to predict the ground motions in the Los Angeles basin for an earthquake on the San Andreas fault more rapidly than the seismic energy can propagate to the basin. This paper is intended to be the first step in testing the credibility of this strategy.

Unfortunately, the whole system can fail for many reasons. Large events require distributed source models that are more complicated than point source models adequate for small
events. For large events it becomes more difficult to separate propagation effects from source effects. The event could occur in a basin. In this case it would be difficult to invert the waveform from the nearest station for source parameters. The USC record of the January 17, 1994 Northridge earthquake is an example of this (Song et al., 1994). A nearby station may also stop working, as happened to the station RPV prior to the Northridge event. We think these problems can be overcome as broadband systems mature and more broadband data is modeled.
PART 2 - PRELIMINARY MODELING OF TKO BROADBAND ARRAY DATA

In this section, we consider some preliminary modeling of a small event recorded by the TKO broadband array, see Figure 11. We have data for two stations from the Kanagawa event, 92/08/15, $M_L = 2.9$. This event is listed in the local seismological report as having a mechanism $ST = 330^\circ$, $DT = 56^\circ$, $RK = 65^\circ$ and a depth of 29 km. A one-dimensional model was constructed to roughly fit the waveforms from this event where concentrate on the early portion of the data, namely P to S, see figure 12 and 13. The model is given at the bottom of Figure 11. These synthetics were generated with the small pulses that occur between P and S. The largest is due to the SV to P conversion occurring between the $\beta = 1.42$ to 0.7 km/sec boundary which probably represents a soft-sedimentary interface. Since the direct SV pulse is not apparent on the vertical, we had to reduce the surface shear velocity to such a low value of 0.7 km/sec. The size of the converted P wave which occurs a second or so ahead of SV is strongly influenced by the local slope of the sediment boundary as well as its sharpness. Thus, we expect to see considerable lateral variations from station-to-station. The data at TOK is clearly higher frequency than at YCU which suggests that the shallow path beneath YCU must be more attenuating. We have simply applied a slightly different source time function to simulate the differences. Accurate descriptions of these effects is possible given the large existing datasets, roughly 70 events ranging in depths from 20 to 100 kms.

The Green's functions for these synthetics is displayed in Figure 14 where we have included the moment and time history. The top two traces are the tangential responses for pure strike-slip and dip-slip mechanisms. The next three traces display the radial responses for strike-slip, dip-slip, and $45^\circ$ dip-slip mechanisms, the standard three fundamental faults. The lower three responses are appropriate for the vertical motions. The set of responses on the left were used in simulating the synthetics in Figures 12 and 13. The middle column shows a set of Green's functions for a larger event and the column on the right a still larger event. As the size increases the near-field becomes more obvious on the broadband motions. This feature is not seen on conventional instruments such as a Wood-Anderson (short-period) as displayed in Figure
15. Figure 16 displays these responses as seen through a long-period torsion instrument with free period 8 seconds. The long-period drift downward becomes more obvious. This particular response is probably similar to the present Kajima instrumentation.

This long-period drift is particularly important in early warning and quite obvious in existing data from large events, see Figure 17.
PART 3 - DEPTH DETERMINATION

The current technique in the Kajima early warning system for estimating the depth of events is based on the ratio of vertical to horizontal amplitudes in the first second of the P waves. This time window avoids complexities in the waveforms for large earthquakes with multiple subevents, but it also misses the information available in other phases of the waveforms. In this section, we discuss waveform features which are diagnostic of earthquake depths. In addition, we indicate travel time characteristics for data from multiple stations that are distinctive for deep events.

WAVEFORM CHARACTERISTICS

The waveform features we will discuss are most stable at longer periods (5 to 10 seconds). Integrating the original waveforms from velocity or acceleration to displacement effectively lowpass filters the data. This increases the prominence of the phases which decay rapidly with depth. Figure 18 shows this effect in synthetic waveforms calculated for a standard one dimensional seismic velocity model.

Two groups of waves, the Pnl waves and the surface waves, are particularly useful as indicators whether an event is deep or shallow. Pnl waves are produced by energy interacting with shallow crustal structure. Figure 19 shows the effects of source depth on this wave group in displacement data from two small earthquakes near Tokyo. The vertical component and the east-west component of records from two stations are displayed in absolute time. Large amplitude Pnl waves are recorded at both YCU and TKO on the vertical component for the shallow event on the S. Izu Peninsula. The east-west components at these stations are naturally rotated into the tangential direction, so the Pnl is not recorded. The radial (north-south) component (not shown) records large amplitude Pnl waves. The deeper event under Tokyo Bay does not produce strong Pnl waves on the vertical components at YCU and HKY. The synthetic waveforms for southern California (Figure 18), suggest that the Pnl should be clearly visible on the vertical and radial
components in displacement records for source depths down to 20 kms. They should fall in amplitude rapidly for sources below the crust.

Surface waves are also strong indicators of source depth. In Figure 19 the Love wave recorded at TKO for the S. Izu Peninsula event is the largest phase on both the vertical and horizontal component. The event under Tokyo Bay does not produce surface waves at either YCU or HKY. The synthetic waveforms in Figure 18 indicate how rapidly surface wave amplitude can decrease as the source depth increases. It is worth noting again here that the surface waves are much more strongly seen in the displacement synthetic waveforms than in the velocity synthetics. Because they are longer period waves, the integration to displacement increases their amplitude relative to the shorter period body waves.

The inclusion of Pnl and surface waves into the early warning system should increase the reliability of depth determination. Rather than using only the mean of the ratio of vertical to horizontal amplitudes, \( (V/H)_{\text{ave}} \), for the first second of P-wave, similar ratios taken over additional windows could be added to the regression. In the current technique, the hypocentral distance is not determined until the S-waves arrive. A window for the Pnl waves, \( (V/H)_{\text{Pnl}} \), would not require waiting longer for data to arrive. If there is enough time after calculating the azimuth to rotate the horizontal component waveforms into the radial and tangential directions, a ratio of the vertical component relative to the tangential component, \( (V/T)_{\text{Pnl}} \), would be more robust. Including a window for surface waves would require waiting after the S-wave for additional data. Also, the location of the window for the surface waves would depend on distance from the source. It would have to be set dynamically, based on the hypocentral distance calculated after the S-wave arrival. Since surface waves appear on all three components, the ratio used on surface waves for depth determination would have be handled differently. The ratio of the amplitude of the surface waves relative to the amplitude of the direct P-wave, \( (SW/P) \), is one possibility. Because of the additional complications of the surface waves, a Pnl window would be the easier suggestion to implement.
Another possible approach to depth estimation is to use relative travel times recorded by various stations. For example, for the Tokyo Bay event in Figure 19, we observe that the time differential between the P-waves at HKY relative to YCU is about 4 seconds. We would predict a value of about 3 seconds from the layered model (under YCU) as discussed in Part 2. A separation of 45 km would map into a difference of about 5 seconds for a shallow event, see Figure 20. These differences are rather small and probably station dependent. Using the combined times of S - P is probably more stable but takes more time for a quick source estimation. Since one measure of S - P is not sufficient information for estimating both distance and depth as presently done, more information must be added to the system. Perhaps the S - P time from the first station in conjunction with the P-wave differential \((P_2 - P_1)\) would be useful if station corrections can be established. But since the azimuth is not known, this is still not enough information. Two measures of S - P are probably necessary to gain some definite improvement over the present procedure, if only timing is used.
REFERENCES


FIGURE 1. A map of southern California with the location of the June 28 1991 Sierra Madre mainshock and the TERRAscope stations used in this study. The source mechanism shown was found by Dreger and Helmberger (1991) with the complete waveforms from these stations and refined Green functions. The black triangles are stations used in the source inversion of the Sierra Madre event. The white triangles are stations are mentioned in the discussion of basin response in the Discussion section.
FIGURE 2. How the estimate of the source mechanism and magnitude of the Sierra Madre mainshock changes with time after the source rupture. The four mechanism correspond to inversions with the data available at that time after the event. The size of the mechanism is proportional to the seismic moment, $M_0$. The source mechanism found with the complete TERRAscope records from PAS, SVD, GSC, ISA, and PFO (Dreger and Helmberger, 1991) is shown in the upper right corner of the figure. The inversions were done using Greens functions calculated from a standard southern California crustal model (Table 1). The Greens functions were calculated for a source of depth 11 km with a triangular source time function lasting 1 second.
FIGURE 3. Data and synthetic waveforms for the inversion using only the PAS Pnl waveforms. The source mechanism found is strike (Φ) = 45°, dip (δ) = 60°, rake (λ) = 155° and seismic moment (M₀) = 7.0 x 10²⁴. The data waveforms for SVD, GSC, ISA and PFO are offset behind those of PAS by the appropriate relative travel time. This indicates when energy arrived at these stations after the Sierra Madre mainshock rupture. The boxes around the Pnl portion of the PAS vertical and radial components indicate the data used for this inversion.
FIGURE 4. Data and synthetic waveforms for the inversion using the entire PAS waveform. The source mechanism found is $\Phi = 120^\circ$, $\delta = 65^\circ$, $\lambda = 120^\circ$ and $M_0 = 3.0 \times 10^{24}$. 
FIGURE 5. Data and synthetic waveforms for the inversion using the entire PAS record and the Pnl portion of the SVD waveforms. The source mechanism found is \( \Phi = 115^\circ, \delta = 65^\circ, \lambda = 110^\circ \) and \( M_0 = 3.6 \times 10^{24} \).
FIGURE 6. Data and synthetic waveforms for the inversion using the entire PAS and SVD records and the Pnl portion of the GSC, ISA and PFO data. The source mechanism found is $\Phi = 95^\circ$, $\delta = 55^\circ$, $\lambda = 105^\circ$ and $M_0 = 3.4 \times 10^{24}$. 
Error of Synthetic Waveforms

FIGURE 7. Error for each solution of synthetic waveforms relative to data for the Sierra Madre mainshock as a function of the amount of data included in the inversion. The white circles show the error for all the data from all the stations. The black circles show the error for only the data included in the inversion.
FIGURE 8. Comparison of a USC tangential displacement record with a convolution of the PAS record with a theoretical response for the Los Angeles basin. The USC and PAS records are from an August 21, 1993 event (M = 4.2) on the San Andreas fault near Palm Springs. The basin response is from Scrivner and Helmberger (1994).
FIGURE 9. Comparison of synthetic waveforms calculated with (a) finite-difference and (b) a hybrid generalized-ray, finite-difference technique.
FIGURE 10. Left panel displays a comparison of the USC data for the Palm Springs event with a synthetic waveform calculated from the two-dimensional model at top left. Right panel displays a comparison of the seismic energy recorded at USC as a function of time (dark line) with the energy predicted by the synthetic waveform.
FIGURE 11. Upper panel displays a rough map of the Kanto Region with the locations of the broadband array and a few event locations. The lower panel displays a crustal model appropriate for YCU where $\alpha$ is the P-wave velocity in km/sec, $\beta$ the S-wave velocity and $\text{Th}$ the layer thicknesses in km.
FIGURE 12. Upper panel displays the three component displacements for the small 1/23/93 event as recorded at YCU ($\Delta = 20$ km). The lower synthetics assume the mechanism given in the local report. Both sets of seismograms are on the same amplitude scale.
FIGURE 13. Modeling results at TOK.

ST = 30°
DP = 50°
RK = 65°
MO = 3.6x10²¹
T = .2 sec
FIGURE 14. Three columns of synthetic displacements are displayed, for $M = 3, 5.5$ and $7$. We assumed a time history of a (0.3,0.3) triangle for the $M = 3$, (0.8,0.8) for the $M = 5.5$, and (4,4) for the $M = 7$. The assumed moments are $3.6 \times 10^{21}$, $10^{24}$, $10^{26}$ respectively. Note the long-period near-field drift.
FIGURE 15. Continuation of Figure 14 as simulated on a short-period Wood-Anderson, (gain = 2800).
Wood-Anderson, LP

FIGURE 16. Continuation of Figure 14 as simulated on a long-period Wood-Anderson, (gain = 1700).
FIGURE 17. Comparison of near-in data and synthetics for the 1993 Kushiro-Oki event, (Takeo, Ide and Yoshida).
FIGURE 18. Synthetic waveforms calculated from a standard southern California seismic velocity model (Table 1) showing waveform variation with source depth from 5km to 17km. Waveforms shown are all for a distance of 100 km and source mechanism of strike = 45°, rake = 90°, dip = 45° and an azimuth of 0° from N. The upper panel shows displacement synthetics. The lower panel shows velocity synthetics for the same model and source configuration.
FIGURE 19. Example of observations of two small events as recorded by the broadband network discussed in Part 2 of this report. These motions are in displacement and are aligned in absolute time. Note that the apparent velocities of the P-waves is about 7.8 km/s for the shallow event and over 11 km/s for the deep event.
FIGURE 20. Travel time plots of the direct P and S-waves appropriate for the YCU model, see Part 2 of this report. The assumed source depths are 7.5 km and 67 km. Note the S - P travel time separation depends on depth.
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Distance and Azimuth from Sierra Madre mainshock for stations used in inversions.
Single-Station Determination of Earthquake Source Parameters

Introduction

Most modern seismic networks use many (10 to 500) stations to determine earthquake source parameters (location, origin time, magnitude). However, a large complex network is potentially vulnerable to a large earthquake within the network. Even if a small portion of the network communication link is disabled by the earthquake, the entire network may lose its function. In contrast, a location method using a single station, or a small number of independent stations, is less vulnerable to failure in the communication link, although its location capability is limited. In the old days of seismology, seismologists like Imamura and Gutenberg extensively used this method for quick reporting purposes. With the advent of high-quality broadband digital seismographic system, we developed a method to emulate this method. A program currently working at the Caltech Seismological Laboratory is called "Gutenberg".

Here we briefly describe this program.

Method

The basic method is schematically shown in Figure 1. Figure 2 shows a three-component broadband seismogram to be illustration purposes.

1. P pick.
   The method for picking P-wave is similar to that described in Allen(1979). We let \( f(t) \) represent the time series for the vertical component seismogram. After removing the mean of \( f(t) \) and any undesirable noise (e.g. micro seismic noise) from \( f(t) \), we generate a test function \( g(t) \) by:

   \[
   f^2(t) + c^2 f^2(t)
   \]

   (1)

   where \( c \) is a constant. This function, \( g(t) \), is a one-sided function of time, shown in Figure 3a.

   We define the long-term average LTA and STA by,

   \[
   LTA(t) = \int_{t-t_1}^{t+t_1} g(t) dt \quad \text{and} \quad STA(t) = \int_{t}^{t+t_s} g(t) dt
   \]

   (2)

   and determine the P arrival time using a criterion

   \[
   \frac{STA(t)}{LTA(t)} \geq \varepsilon
   \]

   (3)

   where \( \varepsilon \) is a preset detection threshold. In the above \( t_1 \) and \( t_s \) are the duration of record used for LTA and STA, respectively.

   A method to discriminate a seismic P phase from glitches is included in the program.
2. Determination of Back Azimuth

We determine the back azimuth from the P-wave polarization angle. When a P arrival is detected, we take a $T_p$ sec of the 3-component record to determine the back azimuth $\phi_s$ as follows.

If the back azimuth is $\phi_s$, the NS and EW component of P wave is given by

$$A_N(t) = -A_p(t)\cos(\phi_s) \quad \text{and} \quad A_E(t) = -A_p(t)\sin(\phi_s)$$ (4)

Thus

$$\phi_s(t) = \tan^{-1}(A_E(t)/A_N(t))$$ (5)

There is an ambiguity of $\pi$ in $\phi_s$ determined by (5). This ambiguity can be removed using the polarity of the vertical component. If the vertical component $A_Z(t)$ is negative, $0 < \phi_s < \pi$; if $A_Z(t)$ is positive, $\pi < \phi_s < 2\pi$.

The back azimuth is determined by taking the time average of $\phi_s(t)$ over $T_p$.

3. Rotation

Once $\phi_s$ is determined, we rotate the NS- and EW-component seismograms into the radial and transverse components, $A_R(t)$ and $A_T(t)$ by,

$$A_R(t) = -A_N(t)\cos(\phi_s) - A_E(t)\sin(\phi_s)$$ (6)

and

$$A_T(t) = -A_N(t)\sin(\phi_s) + A_E(t)\cos(\phi_s)$$ (7)

4. S pick

We use the same method as that used for P pick to determine the arrival time of S wave. Figure 3b shows the test function derived from $A_T(t)$. The only difference is that a fixed long-term average is used for S pick.

5. Epicenter Determination

The epicenter is determined from $\phi_s$ and S-P time. Presently, no provision is made for depth determination.

6. Magnitude

We determine the magnitude from the average amplitude of the 3-component record following P and S. This magnitude is calibrated against $M_L$. Usually, the magnitudes determined from P and S waves are averaged.
7. Results

We have written several programs to process real-time broadband data. The source code of these programs will be provided to Kajima Corporation through Internet. The program has been tested using the records obtained at Pasadena and in the Kanto district. The results are shown in Figures 4, 5, 6, 7, 8, 9, 10, 11, and 12. The parameters used in the program ($\epsilon$, $t_0$, $t_s$, etc) must be adjusted for specific applications and the type of seismograph used.

8. Conclusion

The single-station system works satisfactorily, especially if the distance is less than 120 km. If several stations are used, it will be possible to build a sufficiently reliable system. The merit is that this system does not require a large complex multi-station network. Since each station is essentially independent, the system is robust against failure in communication system, and is desirable for realtime applications.

Figure Caption

Figure 1. Schematic diagram for program "Gutenberg".

Figure 2. Three-component (Vertical, NS, EW) seismogram (velocity) of the 5/28/1993 Bakersfield earthquake ($M=5$) recorded at Pasadena.

Figure 3. Test function $g(t)$ for $P$ pick (a) and $S$ pick (b).

Figure 4. Error in the azimuth determination as a function of epicentral distance.

Figure 5. Error in the epicentral location as a function of epicentral distance.

Figure 6. Comparison of the single-station magnitude with the catalog magnitude.

Figure 7. Velocity seismograms of $M=3.7$ earthquake which occurred on Nov. 23, 1993, in the Kanagawa prefecture. Station YCU.

Figure 8. Test functions for $P$ pick and $S$ pick for the event shown in Figure 7.

Figure 9. Velocity seismograms of $M=3.7$ earthquake which occurred on Nov. 23, 1993, in the Kanagawa prefecture. Station TOK.

Figure 10. Test functions for $P$ pick and $S$ pick for the event shown in Figure 9.

Figure 11. Velocity seismograms of $M=3.7$ earthquake which occurred on Nov. 23, 1993, in the Kanagawa prefecture. Station TKO.

Figure 12. Test functions for $P$ pick and $S$ pick for the event shown in Figure 11.
Determination of Location and Magnitude Using Single 3-Component Station (Program "Gutenberg")

1. P pick
   Use test function:
   \[ f^2(t) + c \cdot \dot{f}^2(t) \]

2. Determine Back Azimuth \( \phi_s \).
3. Determine magnitude, \( M_1 \), from P-wave amplitude.

4. Rotate Seismograms to Transverse Component.

5. S pick

6. Determine Distance from S-P time.

7. Determine magnitude, \( M_2 \), from S-wave amplitude.
a. $g(t)$ for P pick

b. $g(t)$ for S pick

Time, sec
Displacement 112393 05:03:31 TOK

Amplitude, 0.005 cm/div

Time, sec
The diagram shows two curves labeled $e(t)$ and $ep(t)$, with additional curves labeled $es(t)$ and $P$ pick, and $S$ pick. The x-axis represents time in seconds, ranging from 0 to 15. The y-axis is not explicitly labeled but appears to represent some form of data or signal, possibly indicating seismic activity or a similar phenomenon.
The image contains a graph with three lines labeled as follows:

- $e(t)$
- $ep(t)$
- $es(t)$

The graph shows a time axis on the x-axis ranging from 0 to 15 seconds, and a peak labeled 'P pick' near the 5-second mark. Another peak labeled 'S pick' is near the 10-second mark. The graph also includes timestamps and the labeling TKO.
Kajima-CUREe Project

Software Development of an Early Warning System

Final Project Report (Kajima)

Leader  Katsuhisa Kanda
Members  Hiroaki Yamanaka (Dr. Eng.)
         Masamitsu Miyamura (Dr. Eng.)
         Yoshiki Ikeda (Dr. Eng.)
         Takafumi Moroi
Adviser  Takuji Kobori (Prof. Em. Kyoto Univ.)

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**TABLE OF CONTENTS**

1. Introduction 1

2. Overview of the system 4

3. Analysis of recorded data 17

4. Conclusion 30

References 31

Appendix A. A simple algorithm for an early-warning of large events 32

Appendix B. Applications for seismic response controlled structures 34

Appendix C. Comparison of source parameters estimated in the both systems 42
1. INTRODUCTION

Mexico City suffered heavy casualties due to the collapse of buildings caused by the 1985 Michoacan Mexico earthquake. In part because the hypocenter was far from the urban area, many observers note that if even a small amount of information about the earthquake had been made available prior to its arrival at the capital, this could have reduced by a great event the human, material and functional damage suffered by the city. This observation may well apply to Tokyo where the population and public and private establishments have become extremely concentrated, in the event of a major earthquake.

In terms of technical approach, a variety of measures is taken to reduce earthquake damage. The most common is the adoption of seismic resistant designs that ensure the safety of individual buildings by providing their frameworks with as much strength and deformation capability as economically feasible in light of the potential earthquake danger. Beyond the limit of conventional aseismic structural practice, intended only to protect inhabitants by preventing the collapse of a building, the development of seismic response control technology is progressing rapidly. This allows for control over the vibration of a building during an earthquake for such additional goals as maintaining information processing functions and providing a greater sense of security and amenity for the occupants.

Other technologies called early warning systems, are used to immediately halt railway traffic or shut gas lines then vibration beyond a certain level is sensed. Many of these have already reached the stage of being put into practical use by various organizations. They must be also effective to reduce damage of respective functions.

Though studies on techniques for predicting earthquakes are continuing, it must be admitted that short-term earthquake predicting, including scale and effect in addition to time and place, is extremely difficult.

The fact that reliable earthquake predictions cannot be expected in the near future brings the issue of early warning system for earthquake to the fore, because the latter offers much greater potential for quickly realizing practical benefits. The more realistic early warning approach would attempt to detect the occurrence of an earthquake as quickly as possible and rapidly transmit information about the event to locations where it is needed before seismic wave propagates to these locations for use in various damage reduction activities. Even for the information to arrive a mere ten seconds before the earthquake motion struck, knowledge of the earthquake could enable people to begin to flee for safety and make possible a considerable variety of
electrical and mechanical preparations. It can be expected that the scope of applications resulting from this approach will expand tremendously once it is applied in earnest.

This concept was proposed by Hakuno (1972) in Japan. The Railway Technical Research Institute (Nakamura, 1988) has developed an actual system of this kind to ensure the safety of bullet trains during earthquakes: UrEDAS (Urgent Earthquake Detection and Alarm System). This system provides an alarm within a few seconds of the detection of an earthquake event by monitoring seismometers arranged along major railway lines and estimating the magnitude of the earthquake and the location of its hypocenter on the basis of observations of preliminary ground motions. The system then slows or stops trains which are traveling in areas where severe shock is anticipated.

Such concepts have been taken up also in the United States. Kanamori (1991) started under the banner of "Real Time Seismology" to build a system called CUBE. The system is intended to prevent seconds earthquake-related disasters by supplying information about an earthquake immediately after the event and by estimating the damage the earthquake is likely to cause. Bakun et al. (1994) proposed a prototype early warning system for aftershock to reduce the risk especially for the rescue and reconstruction crews working near weakened structures.

The system the authors (Moroi, 1994) have developed (see figure 1) can make known the occurrence of an event before the coming of earthquake ground motion by immediately transmitting information about the event, because it makes full use of highly advanced computer systems and large volume, and high speed data communication techniques. End users can be assumed to be increasingly diverse.

This Kajima-CUREe joint study focuses on the investigation of various kind of issues faced by an early warning system and the modification to improve the accuracy of evaluation.

The authors also think that seismic response controlled structures is one of the most effective application. Several kinds of active control systems have already been applied to actual structures in Japan to suppress vibrations. Most of these systems work based on feedback control laws because of the insensitivity of efficiency to the properties of both a structure and an earthquake, though the feedback control reaches the limit in the efficiency as the level of input motion increases. The feedback-feedforward control which reduces the scale of an input earthquake and improve control efficiency especially in the primary part of shaking, has been studied as an advanced technique. Yang (1987) proposed one control law using instantaneous optimal control, and Suhardjo (1990) implemented another modeling of earthquakes as
a white noise filtered through Kanai spectrum.

This report also addresses the first trial of feedback-feedforward combined control using a "pre-arrival transmission system for earthquake information" in the appendix B.
2. OVERVIEW OF THE SYSTEM

The prototype system forms a communication network around Kanto area, Japan as shown in figures 2-1 and 2-2. It consists of five earthquake detection stations and the Earthquake Information Center at Chofu.

This early warning system can convey information of an earthquake and the predicted seismic intensity that will be expected in the greater Tokyo area by announcements devices or pocket pagers to end users.
Figure 2-2. Component diagram of the system
2.1 Earthquake detection stations.
The intention behind the system now in use is to detect earthquakes occurring in the Tokai region southwest of the capital and send information on them to Tokyo. Earthquake detection stations have been set up from Shimoda to Tokyo, as illustrated in figure 2-1. Each station is equipped with a seismometer, a workstation computer, and communication equipment. The measured ground motions are digitized and analyzed continually. If the threshold level on earthquake detection is exceeded, it concludes that they indicate an earthquake, and this information is reported to the Earthquake Information Center immediately. The remote station also calculates the location of the hypocenter, the magnitude of the earthquake and measured seismic intensity, and transmit these parameters and the seismic waveforms to the Center.

2.2 The Earthquake Information Center.
The Earthquake Information Center is located at intermediate position between the detection stations and end users and can control the input and output of information. When an earthquake occurs, the Earthquake Information Center is capable of monitoring ground motion waveforms and displaying the validity of information on source parameters obtained from each detection station.

2.3 End users and structural response control.
The information is supplied to end users in an intelligible form and as quickly as possible. When an earthquake occurs, the present system notifies users of the time of detection and the name of the detection station, the estimated location and depth of the event and the magnitude, the intensity at each detection station, and predicted seismic intensity at Tokyo by message displays from pocket pagers and synthetic voice signals from announcement device. The predicted ground motion level is transmitted to response controlled buildings by telephone line.

2.4 Packet-switched communication.
The NTT Packet Communication Service (DDX-P) is used in communications between detection stations and the Earthquake Information Center for reporting the occurrence of earthquakes; issuing commands to input wave forms, transmitting the results of calculations, sending wave form data, and so on. Using packet-switched communication, though there is a slight but unavoidable time delay because of the storage time involved in network packet processing, observation can be conducted almost in real time. With regard to communication charges, Packet Communication
Service customers are charged primarily according to the volume of information they transmit, regardless of distance and connection time. This service is therefore appropriate for a network that joins remote locations and in which the frequency of data exchange is comparatively low, as happens in this earthquake observation system.

2.5 Evaluation methods in the information processing.

The observed earthquake waveforms are processed, analyzed and transmitted to users immediately. The technique used for real time evaluation is based on regression analysis of existing earthquake data accumulated as a result of observations in the system. Figure 2-3 shows the flow of the evaluation of source parameters in the system.

(1) Detection of preliminary ground motion of P and S waves.

Since the vertical motion is dominant in the preliminary ground motion of P wave, the characteristic function CFV is defined as (Allen, 1978)

\[ CFV = z_i^2 + k(z_i - z_{i-1})^2 \]  

(1)

where \( z_i \) is the vertical component and \( k \) is a weighting constant. On the contrary, the horizontal motion is dominant in the preliminary ground motion of S wave. Another characteristic function CFH is defined as

\[ CFH = \sqrt{CFX_i \cdot CFY_i} \]  

(2)

where \( CFX_i = x_i^2 + \beta(x_i - x_{i-1})^2 \), \( CFY_i = y_i^2 + \beta(y_i - y_{i-1})^2 \). \( x_i, y_i \) are the orthogonal horizontal components and \( \beta \) is a weighting constant. The parameter which shows the relationship between vertical and horizontal motions is defined as

\[ (V/H)_i = \sqrt{\frac{v_i}{h_i}} \]  

(3)

where \( v_i = z_i^2 + \alpha v_{i-1} \), \( h_i = x_i^2 + y_i^2 + \alpha h_{i-1} \), and \( \alpha \) is a constant. Table 1 shows the detection condition of onset points of P and S waves. Each threshold level is determined depending on site condition.
Evaluation of Source Parameters Using Single 3-component Station
Table 1 Detection condition of onset points of P and S waves

<table>
<thead>
<tr>
<th></th>
<th>P Wave</th>
<th>S Wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>V/H</td>
<td>&gt;σ₁</td>
<td>&lt;σ₂</td>
</tr>
<tr>
<td>CFV</td>
<td>&gt;ε₁</td>
<td></td>
</tr>
<tr>
<td>CFH</td>
<td></td>
<td>&gt;ε₂</td>
</tr>
</tbody>
</table>

(2) Hypocentral Distance.
The hypocentral distance is calculated based on Ohmori Formula (Utsu, 1979).
\[
R = γ T_{S-P}
\]
(4)

where \( T_{S-P} \) is a time difference between the onset points of P and S waves. \( γ \) is a constant (7.6 - 8.7) and obtained from regression analysis for each site.

(3) Epicentral Azimuth.
The azimuth \( θ \) is derived from the following formula (Nakamura, 1983).
\[
θ = \tan^{-1}(X_i/Y_i)
\]
(5)

where \( X_i = x_i z_i + α X_{i-1}, Y_i = y_i z_i + α Y_{i-1} \).

(4) Focal Depth.
The focal depth \( h \) is estimated based on the following regression equation.
\[
Δ/h = b_1 (V/H)_{ave} + b_2
\]
(6)

\( (V/H)_{ave} \) is a mean value of Eq.(3) for first one second of P wave portion. \( Δ \) is a epicentral distance.

(5) Predicted Shaking Level at Tokyo.
The prototype system can predict the seismic intensity \( I_p \) at Tokyo based on estimated hypocentral distances from the detection station \( R_D \), that from Tokyo \( R_F \), and measured seismic intensity \( I_M \) of P wave portion at the detection station as the following equation.
\[
I_p = I_M + c_1 + c_2 \log(R_D) - c_3 \log(R_F)
\]
(7)
c₁, c₂, c₃ are constants obtained from regression analysis, and c₁ is a site-specific value representing site amplification factors. Since the predicted seismic intensity can be evaluated within one second after the detection of S wave near the epicenter, the velocity difference between the propagation of S wave and information transmitting by telephone brings the time for the activity to reduce earthquake damage. If the response controlled structure needs input ground motion acceleration level, Eq. (7) can be modified as follows.

\[ \log(a_P) = \log(a_M) + d_1 + d_2 \log(R_D) - d_3 \log(R_F) \]  \hspace{1cm} (8)

where \(a_P\) is an acceleration predicted at Tokyo and \(a_M\) is an acceleration measured at a detection station.

2.6 Output of the prototype system.
Some moderate earthquakes have occurred since the prototype system was installed in March, 1993. At the time of each of these events, a message indicating the occurrence of the earthquake is displayed on the screen at the Earthquake Information Center within one second of detection at a detection station. As time goes on, various information is displayed, such as (in the order displayed): 1) the first detected ground motion waveform, 2) occurrence time, location of hypocenter, magnitude and measured seismic intensity, 3) predicted seismic intensity for selected areas, 4) location of epicenter on map, and 5) waveforms observed at all detection stations. Furthermore, an announcement unit located in central Tokyo and pocket pagers carried by researchers report the occurrence of the earthquakes. Moments later, 1) Fourier spectra, 2) the distribution map of epicenters, and 3) time-distance curves (recorded waveforms in the hypocentral distance versus time) can be displayed as a manual output. Time-distance curves show the waveforms recorded at five stations in the figure of hypocentral distance versus time. Also, 4) the distribution map of seismic intensity is output. The above confirmed the validity of various data used in conventional earthquake engineering research. Using the example of May 27 earthquake occurring in the east of Tokyo, the first detected waveform at Akasaka is shown in figure 2-4, location of epicenter in the figure 2-5, all recorded waveforms in the figure 2-6, and the off-line output of measured intensity distribution and time-distance curves are shown in figures 2-7 and 2-8 among the items mentioned above. Figure 2-9 is also time-distance curves of Tokaido far off earthquake which we can easily understand why an early warning is faster than the earthquake shaking.
Figure 2-4. The first detected ground motion waveform.
Figure 2-5. Location of epicenter on map.
Figure 2-6. Waveforms observed at all detection stations.
Figure 2-7. Measured seismic intensity at the detection stations.
Figure 2-8. Time-distance curves.
Figure 2-9. Recorded waveforms in the hypocentral distance versus time. The time the earthquake occurred and the velocity at which both P and S waves propagate can be learned by drawing lines among P-wave arrival times and among S-wave arrival times of the waveforms.
3. ANALYSIS OF RECORDED DATA

The system has been operating for more than one year. We have tested the accuracy and rapidity of warnings, and have obtained large amount of recorded data at the five stations. In this section, we modify the parameters for evaluation from the regression analysis and verify the prototype system using these data.

3.1 Outline of observed data.
Table 3-1 and 3-2 list all earthquake events observed in the system from March 1993 to June 1994 except Izu east off Swarm in the end of May 1993. The reason why the swarm earthquake is eliminated for the regression analysis is that most of the earthquake are quite local and peculiar. Figure 3-1(a), (b), (c) shows the location of epicenter classified by the focal depth in the three category. Figure 3-2 shows the seismic intensity in the figure of epicentral distance from Tokyo versus magnitude. Tokyo does not have so large earthquake.

3.2 Analysis of source parameters.
The epicentral distance, magnitude, and focal depth are evaluated with the regression formula obtained from the observed data. The accuracy of evaluation is verified compared to data from Japan Meteorological Agency (JMA) including epicentral azimuth.

(1) Hypocentral distance (Fig.3-3).
The hypocentral distance is evaluated based on Eq.(4). The constant parameter $\gamma$ is given from the observed data as shown in table 3-3. There are some underestimated examples which exceed 200km in epicentral distance. But most of earthquake are correctly evaluated for its hypocentral distance.

(2) Magnitude (Fig.3-4).
Magnitude is estimated based on the attenuation formula as follows

$$ M = P_1 \log(V_{max}) + P_2 \log(R) + P_3 $$

where $P_1$, $P_2$, $P_3$ are constants obtained from regression analysis shown in table 3-3. $P_3$ is a parameter depending on the site condition and seems to have negative correlation with site amplification. Though there is $\pm 1$ error compared to JMA data at most, it
seems to show a good coincidence each other.

Table 3-3 Constants for source parameters

<table>
<thead>
<tr>
<th></th>
<th>$\gamma$</th>
<th>$p_1$</th>
<th>$p_2$</th>
<th>$p_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akasaka</td>
<td>8.694</td>
<td>1.318</td>
<td>2.155</td>
<td>1.585</td>
</tr>
<tr>
<td>Hayama</td>
<td>8.066</td>
<td>2.250</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manazuru</td>
<td>7.640</td>
<td></td>
<td>1.889</td>
<td></td>
</tr>
<tr>
<td>Ito</td>
<td>8.566</td>
<td></td>
<td>2.033</td>
<td></td>
</tr>
<tr>
<td>Shimoda</td>
<td>8.651</td>
<td></td>
<td>2.456</td>
<td></td>
</tr>
</tbody>
</table>

(3) Focal depth(Fig.3-5).
The focal depth is evaluated based on the data observed at Ito station using the Eq.(6). Shallow earthquakes are comparatively corresponding to data from JMA, but the earthquake of about 80km in depth can not be evaluated. It is considered that there is some difficulty to estimate based on Eq.(6).

(4) Epicentral azimuth(Fig.3-6).
There is more than 90° discrepancy between the estimated azimuth and data from JMA. It seems that there are some reason of error to be solved, such as the ill condition of S/N ratio in primary part of shaking, the delay of P-pick, and local site effect.

3.3 Prediction of seismic intensity.
The seismic intensity at Tokyo is estimated from the measured seismic intensity of P-wave portion at Ito station. The results is compared to JMA intensity in figure 3-7. If it is rounded off, 13 among 17 cases is coincident with JMA intensity. It can be considered to be useful for predicted shaking measure.

3.4. Items to be solved in the future
The following issues are intended to be solved in the future.

(1) Improvement of the method to estimate source parameters such as depth and azimuth.

(2) Estimation of source parameters of large earthquakes (See Appendix A.).

(3) Reliability of an early warning system.
<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Epicenter</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth</th>
<th>M</th>
<th>Detection</th>
<th>JMA Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>17-Mar</td>
<td>9:17</td>
<td>Izu Pen. east off</td>
<td>34</td>
<td>57</td>
<td>139</td>
<td>14</td>
<td>4.6</td>
<td>ITO</td>
</tr>
<tr>
<td>19-Mar</td>
<td>14:59</td>
<td>Ibaragi off</td>
<td>36</td>
<td>5</td>
<td>141</td>
<td>39</td>
<td>5.7</td>
<td>AKS</td>
</tr>
<tr>
<td>19-Mar</td>
<td>15:01</td>
<td>Ibaragi off</td>
<td>36</td>
<td>8</td>
<td>141</td>
<td>42</td>
<td>5.5</td>
<td>AKS</td>
</tr>
<tr>
<td>25-Mar</td>
<td>2:09</td>
<td>Izu Pen. south off</td>
<td>34</td>
<td>12</td>
<td>139</td>
<td>8</td>
<td>4.9</td>
<td>SMD</td>
</tr>
<tr>
<td>23-Apr</td>
<td>5:18</td>
<td>Nagano west</td>
<td>35</td>
<td>48</td>
<td>137</td>
<td>30</td>
<td>8.1</td>
<td>SMD</td>
</tr>
<tr>
<td>3-May</td>
<td>4:13</td>
<td>Nagano north</td>
<td>35</td>
<td>51</td>
<td>138</td>
<td>10</td>
<td>5.1</td>
<td>SMD</td>
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<td>7-May</td>
<td>2:23</td>
<td>near Izu-Oshima</td>
<td>34</td>
<td>20</td>
<td>139</td>
<td>17</td>
<td>3.9</td>
<td>SMD</td>
</tr>
<tr>
<td>21-May</td>
<td>11:36</td>
<td>Ibaraki south</td>
<td>36</td>
<td>3</td>
<td>139</td>
<td>54</td>
<td>61.4</td>
<td>AKS</td>
</tr>
<tr>
<td>7-Jun</td>
<td>16:49</td>
<td>Ibaraki south</td>
<td>36</td>
<td>2</td>
<td>141</td>
<td>46</td>
<td>50.9</td>
<td>AKS</td>
</tr>
<tr>
<td>7-Jun</td>
<td>22:14</td>
<td>Kanto far east off</td>
<td>35</td>
<td>21</td>
<td>142</td>
<td>6</td>
<td>52.5</td>
<td>HYM</td>
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<tr>
<td>15-Jun</td>
<td>13:42</td>
<td>Kanto far east off</td>
<td>34</td>
<td>48</td>
<td>142</td>
<td>6</td>
<td>56.5</td>
<td>AKS</td>
</tr>
<tr>
<td>11-Jul</td>
<td>5:02</td>
<td>Tokaido far off</td>
<td>33</td>
<td>51</td>
<td>138</td>
<td>48</td>
<td>26.9</td>
<td>SMD</td>
</tr>
<tr>
<td>11-Jul</td>
<td>6:54</td>
<td>Tokaido far off</td>
<td>33</td>
<td>51</td>
<td>138</td>
<td>48</td>
<td>25.4</td>
<td>SMD</td>
</tr>
<tr>
<td>11-Jul</td>
<td>21:23</td>
<td>Tokaido far off</td>
<td>33</td>
<td>51</td>
<td>138</td>
<td>48</td>
<td>24.4</td>
<td>SMD</td>
</tr>
<tr>
<td>12-Jul</td>
<td>0:58</td>
<td>Tokaido far off</td>
<td>33</td>
<td>52</td>
<td>138</td>
<td>50</td>
<td>26.4</td>
<td>SMD</td>
</tr>
<tr>
<td>12-Jul</td>
<td>22:17</td>
<td>Hokkaido SW. off</td>
<td>42</td>
<td>41</td>
<td>139</td>
<td>12</td>
<td>34.7</td>
<td>AKS</td>
</tr>
<tr>
<td>17-Jul</td>
<td>21:34</td>
<td>near Hachijo Island</td>
<td>33</td>
<td>16</td>
<td>140</td>
<td>50</td>
<td>37.5</td>
<td>SMD</td>
</tr>
<tr>
<td>23-Jul</td>
<td>16:33</td>
<td>Tokyo Bay</td>
<td>35</td>
<td>37</td>
<td>140</td>
<td>7</td>
<td>83.4</td>
<td>AKS</td>
</tr>
<tr>
<td>26-Jul</td>
<td>3:29</td>
<td>Izu Pen. east off</td>
<td>34</td>
<td>58</td>
<td>139</td>
<td>10</td>
<td>5.3</td>
<td>ITO</td>
</tr>
<tr>
<td>26-Jul</td>
<td>3:29</td>
<td>Izu Pen. east off</td>
<td>34</td>
<td>58</td>
<td>139</td>
<td>10</td>
<td>4.3</td>
<td>SMD</td>
</tr>
<tr>
<td>26-Jul</td>
<td>3:32</td>
<td>Izu Pen. east off</td>
<td>34</td>
<td>59</td>
<td>139</td>
<td>10</td>
<td>7.3</td>
<td>ITO</td>
</tr>
<tr>
<td>28-Jul</td>
<td>0:23</td>
<td>Izu Pen. east off</td>
<td>34</td>
<td>58</td>
<td>139</td>
<td>5</td>
<td>4.3</td>
<td>ITO</td>
</tr>
<tr>
<td>8-Aug</td>
<td>4:42</td>
<td>Hokkaido SW. off</td>
<td>41</td>
<td>57</td>
<td>139</td>
<td>53</td>
<td>26.6</td>
<td>AKS</td>
</tr>
<tr>
<td>8-Aug</td>
<td>17:34</td>
<td>Mariana Islands</td>
<td>13</td>
<td>0</td>
<td>144</td>
<td>42</td>
<td>61.8</td>
<td>HYM</td>
</tr>
<tr>
<td>18-Sep</td>
<td>11:18</td>
<td>Ibaragi off</td>
<td>36</td>
<td>11</td>
<td>140</td>
<td>53</td>
<td>35.4</td>
<td>AKS</td>
</tr>
<tr>
<td>12-Oct</td>
<td>0:55</td>
<td>Tokaido far off</td>
<td>32</td>
<td>1</td>
<td>138</td>
<td>14</td>
<td>388.7</td>
<td>ITO</td>
</tr>
<tr>
<td>1-Nov</td>
<td>21:22</td>
<td>Ibaragi South</td>
<td>36</td>
<td>6</td>
<td>140</td>
<td>14</td>
<td>82.4</td>
<td>AKS</td>
</tr>
<tr>
<td>9-Nov</td>
<td>5:49</td>
<td>Ibaragi off</td>
<td>36</td>
<td>13</td>
<td>141</td>
<td>50</td>
<td>46.5</td>
<td>AKS</td>
</tr>
<tr>
<td>21-Nov</td>
<td>16:19</td>
<td>Ibaragi off</td>
<td>36</td>
<td>27</td>
<td>141</td>
<td>9</td>
<td>35.4</td>
<td>AKS</td>
</tr>
<tr>
<td>23-Nov</td>
<td>5:03</td>
<td>Kanagawa east</td>
<td>35</td>
<td>28</td>
<td>139</td>
<td>37</td>
<td>38.3</td>
<td>AKS</td>
</tr>
<tr>
<td>23-Nov</td>
<td>12:40</td>
<td>Kanagawa east</td>
<td>35</td>
<td>29</td>
<td>139</td>
<td>38</td>
<td>36.3</td>
<td>AKS</td>
</tr>
</tbody>
</table>

Data are based on JMA report.
TKO:Tokyo YKO:Yokohama AJR:Ajiro
AKS:Akasaka,Tokyo HYM:Hayama MNZ:Manazuru ITO:Ito SMD:Shimoda
Table 3-2 List of Earthquake Events Observed in the System (Jan.-June 1994)

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Epicenter</th>
<th>Latitude Deg. Min.</th>
<th>Longitude Deg. Min.</th>
<th>Depth km</th>
<th>M</th>
<th>Detection Point</th>
<th>JMA Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>23-Jan</td>
<td>12:17</td>
<td>Izu Pen. east off</td>
<td>35 0</td>
<td>139 11</td>
<td>5</td>
<td>2.8</td>
<td>ITO</td>
<td>1</td>
</tr>
<tr>
<td>23-Jan</td>
<td>15:43</td>
<td>Ibaragi south-west</td>
<td>36 19</td>
<td>140 5</td>
<td>77</td>
<td>4.4</td>
<td>AKS</td>
<td>2 1 1</td>
</tr>
<tr>
<td>16-Feb</td>
<td>12:38</td>
<td>Ibaragi south-west</td>
<td>35 58</td>
<td>140 6</td>
<td>81</td>
<td>4.2</td>
<td>AKS</td>
<td>2 1 1</td>
</tr>
<tr>
<td>11-Mar</td>
<td>12:12</td>
<td>near Izu-oshima Isl.</td>
<td>34 18</td>
<td>139 12</td>
<td>2</td>
<td>5.3</td>
<td>SMD</td>
<td></td>
</tr>
<tr>
<td>11-Mar</td>
<td>12:54</td>
<td>near Izu-oshima Isl.</td>
<td>34 19</td>
<td>139 11</td>
<td>5</td>
<td>4.3</td>
<td>SMD</td>
<td></td>
</tr>
<tr>
<td>11-Mar</td>
<td>13:38</td>
<td>near Izu-oshima Isl.</td>
<td>34 18</td>
<td>139 11</td>
<td>5</td>
<td>5.1</td>
<td>SMD</td>
<td></td>
</tr>
<tr>
<td>12-Mar</td>
<td>19:08</td>
<td>near Izu-oshima Isl.</td>
<td>34 25</td>
<td>139 16</td>
<td>6</td>
<td>4.2</td>
<td>SMD</td>
<td>1</td>
</tr>
<tr>
<td>16-Mar</td>
<td>21:09</td>
<td>near Izu-oshima Isl.</td>
<td>34 19</td>
<td>139 8</td>
<td>4</td>
<td>4.7</td>
<td>SMD</td>
<td></td>
</tr>
<tr>
<td>8-Apr</td>
<td>10:10</td>
<td>Sanriku far off</td>
<td>40 32</td>
<td>143 53</td>
<td>9</td>
<td>6.6</td>
<td>AKS</td>
<td></td>
</tr>
<tr>
<td>27-May</td>
<td>23:53</td>
<td>Tokyo east</td>
<td>35 42</td>
<td>139 42</td>
<td>42</td>
<td>4.0</td>
<td>AKS</td>
<td>3 2 1</td>
</tr>
<tr>
<td>14-Jun</td>
<td>5:55</td>
<td>Izu Pen. south off</td>
<td>34 25</td>
<td>139 1</td>
<td>2</td>
<td>4.0</td>
<td>SMD</td>
<td></td>
</tr>
<tr>
<td>17-Jun</td>
<td>8:15</td>
<td>Kanagawa west</td>
<td>35 23</td>
<td>139 0</td>
<td>12</td>
<td>3.1</td>
<td>MNZ</td>
<td></td>
</tr>
<tr>
<td>29-Jun</td>
<td>6:54</td>
<td>Chiba south</td>
<td>34 57</td>
<td>139 53</td>
<td>60</td>
<td>5.2</td>
<td>HYM</td>
<td>3 3 4</td>
</tr>
</tbody>
</table>

Data are based on JMA report.

TKO: Tokyo YKO: Yokohama AJR: Ajiro
AKS: Akasaka, Tokyo HYM: Hayama MNZ: Manazuru ITO: Ito SMD: Shimoda
Figure 3-1(a) The location of epicenter (Depth 0<h<10km).
Figure 3-1(b) The location of epicenter (Depth $10 < h < 50$ km).
Figure 3-1(c) The location of epicenter (Depth h>50km).
Figure 3-2 Seismic intensity in the epicentral distance from Tokyo versus magnitude.
Figure 3-3 Estimated hypocentral distance compared to JMA.
Figure 3-4 Estimated magnitude compared to JMA.
Figure 3-5 Estimated focal depth compared to JMA.
Figure 3-6 Estimated epicentral azimuth compared to JMA.
Figure 3-7 Predicted seismic intensity at Tokyo compared to JMA.
4. CONCLUSIONS

The first stage of constructing a new early warning system, "pre-arrival transmission system for earthquake information," has been completed. The prototype system has been operating reliably for about one year, has accumulated its observed data, and has been modified to promote the evaluation accuracy based on observed data in the system. But there remains some tasks to be solved for a practical use.
REFERENCES

9. Utsu, (1979), Seismology, Kyouritsu Publisher (in Japanese)
Appendix A:
A SIMPLE ALGORITHM FOR AN EARLY WARNING OF LARGE EVENTS

This system has 5 local detection stations and an earthquake information center. Each local station estimates location and magnitude of an event in real time when the ground motion exceeds triggering level, while the center collects earthquake data observed at the local stations by ISDN network. Our system can estimate earthquake parameters for small and moderate earthquakes reliably. It, however, may not work well during a large earthquake. We are now developing a simple and robust procedure providing an early-warning method for a large earthquake. By incorporating this procedure, our system will be able to work even during a large event, though detail information on earthquake cannot be obtained immediately.

We define a kind of small or moderate earthquakes as a class 1 event. The proposed system has additional procedure for a class 2 event defined as a large event like M8 class earthquakes. The additional procedure is as follows;

After triggering at the P-wave onset, we monitor the amplitudes in the three components at each local station. When the amplitudes (or two horizontal amplitudes) are beyond a certain threshold level that is enough large over a certain time interval. The threshold level can be determined by considering statistically expected maximum velocity values. As soon as the threshold level exceeds, the local station sends a real-time flag signal indicating the observation of large ground motion at the station. When the central station receives the flag signals from more than two local stations, the central station declare the occurrence of a large earthquake near the local stations. After sending the flag signal, each local station works normally without regard whether the event belongs to class 1 or 2. Only the central station can judge the class of an event and send warning for large earthquakes to end-users.
A simple algorithm for an early-warning of large events

Local Detection Station

trigger by P-wave onset

data input

NO

Detect S-wave onset

YES

source parameters (class 1)

NO

end of event

YES

Earthquake Information Center

occurrence of event

NO

large motion at more than 2 local stations

YES

Earthquake Information Center

observation of large motion

YES

declare occurrence of large event (class 2)

alarm

end
Appendix B: APPLICATIONS FOR SEISMIC RESPONSE CONTROLLED STRUCTURES

There are great opportunities for effective use of information obtained from this system. But since the distribution and utilization of information provided by the system is likely to have great impact on society in many ways and with respect to various problems, the scope of system applications should be given careful consideration. From this point of view, the seismic response controlled structure is indicated to be one of the most effective applications.

B.1 Pre-arrival Information for Response Controlled Structure.
If the early warning system can supply information on an impending earthquake as early as possible to a dynamic intelligent building with active controllers as shown in figure 5, more effective control of the building will become possible.

![Diagram of application to response controlled structure](image)

Figure B-1. Application to response controlled structure
For such a building supplied with a feed from the system, the information on a coming earthquake motion could be used at the following three levels.

(1) Earthquake occurrence information:
Simple information that an earthquake is imminent is used as a trigger signal for seismic response controllers. For example, though base-isolated structures are said to be generally unfavorable in strong winds, they could be used to make possible the design of a building whose base is firmly fixed in ordinary circumstances. But, when a trigger signal is transmitted from the early warning system, they can quickly modify themselves such that a base-isolation mechanism is put into operation. It is also effective to active mass damper/driver (AMD) systems. It gives more time than the trigger signal from the sensor installed at the base of a building, and the AMD system may be powered off in ordinary condition but be powered on by the signal in order to save electricity.

(2) Frequency contents of ground motion:
The frequency characteristics of ground motion depend on source mechanism, wave propagation characteristics and local soil profile, and it can be predicted based on the observed ground motion at a remote detection station taking account of wave propagation characteristics and local soil profile. If the predicted dominant frequency is supplied to active variable stiffness (AVS) systems, it is useful information for the initial control settings and the schedule of stiffness selection.

(3) Amplitude of ground motion:
If the waveforms are perfectly predicted, the input motion to the structure can be effectively reduce based on the feedforward control algorithm. But, since the phase of the ground motion waveform is greatly affected by local soil profile, predicted waveform is not valid at this moment. The envelope shape, amplitude level of ground motion, and the onset time of P-wave and S-wave may be, however, expected to be predicted in a certain accuracy. The effectiveness of these pre-arrival information is discussed in the following section.

B.2 Control Algorithm.
When a SDOF linear structure is actively controlled by a control force, the motion of equation is expressed as follows.
where $h$ and $\omega$ are the damping ratio and the natural circular frequency of the structure, respectively. $q(t)$ is the relative displacement to the base and $\ddot{y}(t)$ is the acceleration at the base. $u_N(t)$ is the control force normalized by the mass of the structure. Assuming that the control force is regulated linearly by the relative velocity and displacement of the structure and the acceleration at the base, the feedback-feedforward control law is represented as Eq. (B-2).

$$u_N(t) = g_v(t)q(t) + g_d(t)q(t) + g_f(t)\ddot{y}(t)$$  \hspace{1cm} (B-2)

Substituting Eq. (B-2) into Eq. (B-1), the motion of equation is rewritten as follows.

$$\ddot{q}(t) + [2h\omega - g_v(t)]\dot{q}(t) + [\omega^2 - g_d(t)]q(t) = [g_f(t) - 1]\ddot{y}(t)$$  \hspace{1cm} (B-3)

Therefore, the feedback gain $g_v(t)$ demands the condition of $g_v(t) < 0$ to add a damping to a structure, and the feedforward gain $g_f(t)$ demands $0 < g_f(t) < 1$ to reduce the scale of an input earthquake. Assuming that the gains keep constant values in the a sampling time interval $\Delta t$, the state equation is represented in the discrete time-space.

$$x(k-1) = Ax(k) + Bu_N(k) + Dy(k)$$  \hspace{1cm} (B-4)

The control law Eq. (B-2) is approximately rewritten using a one-step delay information.

$$u_N(k) = g_v(k)\dot{q}(k-1) + g_d(k)q(k-1) + g_f(k)\ddot{y}(k-1)$$  \hspace{1cm} (B-5)

In this study, since velocity-feedback term easily makes control more insensitive to the nature of earthquake and keeps it more stable, the feedback gain $g_v$ keeps constant to add an unchangeable damping to a structure. But the gain $g_d$ keeps zero, because the effectiveness of displacement-feedback is less than that of velocity-feedback. Feedforward control makes up feedback control because only velocity-feedback reaches at the limit in the control efficiency. The pre-arrival earthquake information determines the feedforward gain $g_f$ and predicts the acceleration at the base if $\ddot{y}(k)$ is not obtained.

**B.3 Simulation Analysis.**
The various kinds of feedback-feedforward control (Table B-1) are analyzed to be compared with no control (NC) and only feedback control (FB) from the point of the seismic response. The total control force $u_N(k)$ is limited to $\alpha$ time of the gravity at most ($\pm \alpha g$). The feedback control has priority over the control force assignment. If the feedback control force reaches maximum control force, the feedforward gain $g_F$ is enforced to be zero.

Table B-1. Analytical cases for feedback-feedforward control

<table>
<thead>
<tr>
<th>Case</th>
<th>Input Acceleration $\ddot{y},(k)$ for Control</th>
<th>Gain $g_F(k)$ ($0 &lt; g_F(t) &lt; 1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF1</td>
<td>Observed Base Accel. $\ddot{y}_o(k)$</td>
<td>$[\pm \alpha g - gV(k) \dot{q}(k-1)]/\ddot{y}_o(k-1)$</td>
</tr>
<tr>
<td>FF2</td>
<td>Remote Ground Motion.$\beta \ddot{y}_R(k)$</td>
<td>$[\pm \alpha g - gV(k) \dot{q}(k-1)]/\beta \ddot{y}_R(k-1)$</td>
</tr>
<tr>
<td>FF3</td>
<td>Observed Base Accel. $\ddot{y}_o(k)$</td>
<td>$[\pm \alpha g - gV(k) \dot{q}(k-1)]/\ddot{y}_o(k-1)$</td>
</tr>
<tr>
<td>FF4</td>
<td>Predicted Base Accel. $\ddot{y}_p(k)$ generated with $\text{Envelop}[\text{Eq.(8)}]$ and $\text{Sign}[\ddot{y}_o(k)]$</td>
<td>$[\pm \alpha g - gV(k) \dot{q}(k-1)]/\ddot{y}_p(k-1)$</td>
</tr>
</tbody>
</table>

* $\ddot{y}_R$ : acceleration observed at Manazuru station, $b=a_0/a_M$ (See Eq.(8))

A SDOF($T=0.5\text{sec}, h=0.01$) model is used for the simulation of seismic response. The value of $a$ is assumed to be 0.1 so that we can clearly recognize the difference of effectiveness of each case, though it is relatively large compared to practical cases. Three events observed by the pre-arrival transmission system are adopted and their amplitude are magnified to be 200-300 cm/sec$^2$ in maximum acceleration. The results are shown in table B-2 and figure B-2 for maximum responses, and in figure B-3(a),(b) for displacement time history.

Table B-2. Comparison of maximum responses

<table>
<thead>
<tr>
<th>Case</th>
<th>93/7/11 Accel.</th>
<th>93/7/17 Accel.</th>
<th>93/10/12 Accel.</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>809</td>
<td>5.12</td>
<td>1137</td>
</tr>
<tr>
<td>FB</td>
<td>250</td>
<td>1.59</td>
<td>437</td>
</tr>
<tr>
<td>FF1</td>
<td>104</td>
<td>0.41</td>
<td>214</td>
</tr>
<tr>
<td>FF2</td>
<td>248</td>
<td>1.55</td>
<td>402</td>
</tr>
<tr>
<td>FF3</td>
<td>192</td>
<td>1.22</td>
<td>289</td>
</tr>
<tr>
<td>FF4</td>
<td>180</td>
<td>0.84</td>
<td>271</td>
</tr>
</tbody>
</table>
Figure B-2 Maximum response ratio to that of no control case (Displacement)
Figure B-3.(a) Time history of response displacement (93/7/17 near Hachijo Island)
Figure B-3.(b) Time history of response displacement (93/10/12 Tokaido far off)
FF1 is considered to be an ideal case under the given condition and obtains large reduction rate of responses. FF2 case which directly uses the remote recorded time history adjusted for its onset time of S-wave, shows little effectiveness in maximum response values compared to FB case, but in the comparison of time history, responses are reduced especially in primary shaking part. FF3 and FF4 shows intermediate effectiveness among the feedback-feedforward controls. It implies that the sign of input motion for feedforward control is significant to reduce the structural responses.

**B.4 Conclusion**

If the predicted input ground motion to the controlled structure is adopted in the feedback-feedforward control algorithm, the control force can activate more effectively than that of the feedback control and can reduce the response of the structure.
Appendix C:
COMPARISON OF SOURCE PARAMETERS ESTIMATED IN THE BOTH SYSTEMS.

The errors of estimated source parameters are considered to be due to local site effects and the methodology for estimation. As for the local site effects, we should select relatively hard rock site with flat surface, but some of the local station are located on soft soil and their estimated parameters may be unreliable. In this appendix, the discrepancy due to estimated methods of Kajima and 'Gutenberg(Caltech)' are checked by using data recorded at hard soil site in the Kajima’s early warning network.

We select 5 events recorded at Shimoda in the south end of Izu Peninsula as follows.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Epicenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>93/3/25</td>
<td>2:09</td>
<td>Izu Peninsula Off</td>
</tr>
<tr>
<td>93/7/11</td>
<td>5:03</td>
<td>Tokaido Far Off</td>
</tr>
<tr>
<td>93/7/11</td>
<td>6:54</td>
<td>Tokaido Far Off</td>
</tr>
<tr>
<td>93/7/12</td>
<td>0:58</td>
<td>Tokaido Far Off</td>
</tr>
<tr>
<td>94/3/11</td>
<td>13:38</td>
<td>Near Izu Ohshima Island</td>
</tr>
</tbody>
</table>

The epicenter of these events are located in the Pacific region, and the hypocenters are relatively shallow within 30km in focal depth.

The estimated parameters for comparative study are epicentral distance, azimuth and magnitude. And JMA data are listed for reference.
Table C.2  Comparison of estimated parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Event</th>
<th>Kajima</th>
<th>Gutenberg</th>
<th>JMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ(km)</td>
<td>93/3/25</td>
<td>50</td>
<td>50</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>93/7/11a</td>
<td>88</td>
<td>82</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>93/7/11b</td>
<td>89</td>
<td>84</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>93/7/12</td>
<td>88</td>
<td>79</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>94/3/11</td>
<td>44</td>
<td>36</td>
<td>47</td>
</tr>
<tr>
<td>Azimuth</td>
<td>93/3/25</td>
<td>204</td>
<td>184</td>
<td>157</td>
</tr>
<tr>
<td>(degree)</td>
<td>93/7/11a</td>
<td>227</td>
<td>207</td>
<td>186</td>
</tr>
<tr>
<td></td>
<td>93/7/11b</td>
<td>232</td>
<td>216</td>
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Recorded data includes high frequency contents compared to TERRAscope data and are not filtered. So we set a triggering level of 0.001 cm/sec. for P-pick of Gutenberg. Gutenberg detects P-pick little bit late compared to Kajima in the case of event 94/3/11. This is why the Gutenberg result of event 94/3/11 is not so good. Since the epicentral distance and magnitude are estimated based on the regression formula, the Gutenberg should be tuned for Kanto area in Japan. But, there is not so big discrepancy between Kajima and Gutenberg except the 94/3/11 event.

**Comments from Professor Kanamori**

I think that the agreement is very good. All the constants used in qqt are adjusted for TERRAscope type instruments and for California so it may require some adjustments for better performance. They were tentatively adjusted for California, and would need to be modified. But so far everything looks O.K. to me.

One thing I noticed is the systematic difference in azimuth. (Kajima>CUBE>JMA always except 3/11 for which the p pick is wrong). Probably this is due to the lateral heterogeneity of the structure. In my program the azimuth is determined with the data
having very short duration, and simple polarization is used. I wonder if the difference is mainly due to the length of the data used for azimuth determination. If the structure is heterogeneous, the path is off great circle and the deviation from great circle gets usually larger after P wave arrival.