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A STUDY OF A TECHNOLOGY FOR OPTIMIZING DESIGN OF MICROEARTHQUAKE MONITORING NETWORK SYSTEMS IN GEOTHERMAL FIELDS

Satoshi Shigehara[1], Mineyuki Hanano[2], Masayuki Tateno[1], Takashi Kuwano[1] and Shigeyuki Yamazawa[3]

1 JMC Geothermal Engineering Co.,Ltd.,72-2 Sasamori, Ukai, Takizawa-mura, Iwate, 020-0172 Japan
2 Japan Metals and Chemicals Co.,Ltd.,1-3-6 Saien, Morioka-shi, Iwate, 020-0024 Japan
3 New Energy and Industrial Technology Development Organization, 3-1-1, Higashi-ikebukuro, Toshima-ku, Tokyo, 170-6030 Japan

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ABSTRACT

Microearthquakes are triggered in geothermal fields when fluids are withdrawn from or re-injected into geothermal reservoirs. Using microearthquake monitoring, it is possible to delineate geothermal reservoir boundaries and the flow paths of geothermal fluids by precisely measuring changes in the distribution of microearthquake hypocenters. To accurately locate the hypocenters, it is essential to design an optimum microearthquake monitoring network system. For this purpose a conceptual design of a microearthquake monitoring system, to detect changes in heat and mass flow in geothermal reservoirs, was studied. In order optimize a microearthquake monitoring network, we conducted a detectability simulation, a hypocentral accuracy simulation and a sensitivity study on the Kakkonda network of stations. Consequently, it was proved that the detectability and hypocentral accuracy simulations are very effective for designing the best possible network. We confirmed that the detectability simulation is reliable by comparing its results to observed microearthquakes in the Kakkonda field. We also established general guidelines in designing a network of seismic stations.

1. INTRODUCTION

Geothermal fluid flow induces numerous microearthquakes in many geothermal fields. To understand the characteristics of a geothermal reservoir, it is essential to find out time-lapse changes in the reservoir using microearthquake occurrences within the field. In The Geysers, California, Foulger *et al* (1997) conducted Vp/Vs tomographic inversion studies using microearthquake data from 1991 and 1994, separately, to detect changes in Vp/Vs within the reservoir. In the Kakkonda geothermal field, northern Honshu, Japan, Tosha *et al* (1993) found that seismicity increased when fluid circulation was stopped during the annual inspection period of the power plants, suggesting that the occurrence of microearthquakes is related to fluid flow changes. However only a few number of studies, so far, have been done on geothermal time-lapse changes using microearthquakes.

We need both permanent and temporal seismic monitoring networks with enough detection ability (detectability) and accuracy in locating hypocenters (hypocentral accuracy) to detect time-lapse changes in a geothermal reservoir using microearthquakes. We designed specifications for such a network of stations by simulating detectability and hypocentral accuracy of the monitoring network in the Kakkonda field. Then we examined guidelines in designing a network of stations to detect changes in reservoir conditions. As a result, it was proved that the detectability and hypocentral accuracy simulations are very effective in verifying if a network of stations could attain the requisite microearthquake detectability and hypocentral accuracy before installation of the network. We also derived general guidelines for designing an optimum network of seismic stations.

2. DESIGNING A PERMANENT AND TEMPORAL NETWORK OF SEISMIC STATIONS

The basic sequence of tasks in planning a permanent and temporal network of stations to detect reservoir changes in geothermal fields is as follows (Figure 1):

- Set the desired Magnitude minimum and hypocenter accuracy to detect reservoir changes.
- Make a preliminary design of the monitoring network which satisfies the budget, taking into account the known distribution of seismicity, volume of the reservoir, etc. Measure ground noise or make preliminary microearthquake observations.
- Pinpoint the location of permanent and temporal stations and set the desired accuracy of observation. Then simulate detectability and hypocentral accuracy. Examine the geometry of permanent stations, to monitor changes in the distribution of seismicity over a long period of time, and the number of temporal stations needed to observe temporal changes in velocity structures. The distribution of stations is also useful in analyzing three dimensional velocity structures.
- If the proposed network of stations does not have enough observational accuracy based on the simulation studies, change the network.
- When the observation accuracy is deemed sufficient, examine and decide the optimum method and equipment necessary for the network, within the limits of the budget. During this process, research the specifications of seismometers, transmission devices and data acquisition devices, and examine digital data conversion methods of transmitting, recording and timing.

3. METHODS OF SIMULATION

In this section, we discuss detectability and hypocentral accuracy simulation methods using a function from the Microearthquake Processing and Analyzing System (MEPAS) (Miyazaki *et al*, 1995).

3.1 The detectability simulation method

Input data to the detectability simulation are the trigger levels (velocity amplitudes) of all stations and the trigger condition. The selected trigger levels are compared with estimated velocity amplitudes which will be recorded at stations. Finally minimum magnitudes which will be recorded in the network under the trigger condition are calculated. For velocity amplitude estimates we use the equation below, from Watanabe (1971). Velocity amplitudes are calculated at $20\times 20\times 20$ grid points in the three dimensional target area.

$$0.85M - 2.50 = \log(A) + 1.73\log(R) \qquad (1)$$

A: maximum velocity amplitude (x 10^{-2}m/sec)
M: magnitude of earthquake
R: hypocentral distance (km)

3.2 The hypocentral accuracy simulation method

Data used in the hypocentral accuracy simulation include the degree of error in determining the initial arrival times of P- and S-waves, station coordinates and the velocity model. Standard deviations of the original elements are estimated from the regular equation by the least square method in the hypocenter determination. Errors of original elements are calculated at 20 $\times$20$\times$20 grid points in the three dimensional target area. This method is based on Peters and Crosson (1972). However the hypocentral accuracy simulator function in the MEPAS takes into account the picking error of the S-wave and errors in the thickness of velocity layers that Peters and Crosson (1972) did not deal with.

4. THE SEISMIC MONITORING NETWORK IN THE KAKKONDA GEOTHERMAL FIELD

In the Kakkonda geothermal field, microearthquake monitoring was conducted by NEDO between November 25, 1994 and March 31, 1999 within the project 'Deep-seated Geothermal Reservoir Survey. Figure 2 shows the location of seismic stations. This network consists of ten stations (KM-1 to KM-10). Three component, resonant frequency 2Hz, velocity-type seismometers (MarkProducts L-22) are installed at each station. Seismometers at three stations (KM-5, KM-6, KM-10) are installed on the surface and the others, near the bottom of an observation well of about 50m depth. Seismic signals are recorded if signals at three stations or more exceed their trigger level. Signals are converted to digital through a 16 bit A/D converter at a sampling frequency of 1000Hz. Background noise ranges from 1×10^{-7} to 1×10^{-6}m/s. For hypocenter determination, we use a horizontal six-layered velocity model that was estimated by one-dimensional velocity structure inversion. Station coordinates are measured by the open traverse survey, therefore the errors of station coordinates are estimated to be less than a few meters.

5. SETTING AN OBJECTIVE

A shallow reservoir exists about 1.5km deep in the Kakkonda field. We usually set the drilling target as a sphere with a radius of about 100m. At Kakkonda, a few thousands of earthquakes are recorded in a year. Therefore we set our guidelines to detect reservoir condition changes as follows: detection of microearthquakes with magnitudes >-1 within the network which covers the geothermal reservoir and occurs shallower than 1.5km and microearthquake hypocenters with horizontal and vertical errors within 100 meters.

6. THE DETECTABILITY AND HYPOCENTRAL ACCURACY SIMULATIONS

6.1 Setting simulation parameters

We set basic parameters for the detectability and hypocentral accuracy simulations based on the results of microearthquake monitoring in the Kakkonda field (Table 1).

Parameters used in the detectability simulation are the trigger condition and the trigger levels. The trigger condition is the same as the Kakkonda monitoring network. The trigger levels of all stations are determined to have amplitudes between 5×10^{-7} and 2×10^{-6}m/s, close to the noise levels, so that as little noise data as possible are recorded and microearthquake signals are recorded as much as possible. In the Kakkonda field we set trigger levels at two or three times the maximum amplitude of noise.

Errors in picking P- and S-waves are determined at 5m/sec and 20m/sec, respectively, based on observations in the Kakkonda field. Errors in station coordinates are determined at 10m, taking into account the survey method used in setting the coordinates. Errors of P- and S-wave velocities are set at 0km/sec and errors in the thickness of velocity layers are set at 0km because the real velocity structure is unclear here.

6.2 Detectability simulation results

Figure 3 shows an example of detectability simulation results. This indicates how much detectability would improve if stations are added to the Kakkonda network. The upper figure (1) shows detectability if the network consists of eight stations without KM-9 and KM-10 at the NW part of the network. The middle figure (2) shows detectability if the network has ten stations including KM-9 and KM-10. The lower figure (3) shows detectability if the network has eleven stations, with one station added near the Kakkonda geothermal power plant. These figures show the distribution of expected minimum microearthquake magnitudes that can be recorded by each seismic network as a contour diagram. In the upper figure (1) the contour of magnitude -1.2 just covers the seismic network. In the middle figure (2), the contour of -1.4 in the NW part and the contour of -1.2 spreads out, so detectability is improved. In the lower figure (3), the contour of -1.4 spreads more widely and the -1.2 contour covers the whole area.

As these detectability simulation results imply, we can verify improvement in detectability by adding stations to an imaginary network prior to installation. This is very useful in examining and optimizing the arrangement and setting of stations, trigger condition, trigger level and ground noise reduction to attain the intended detectability by taking the budget into account.

6.3 Results of the hypocentral accuracy simulation

Figure 4 shows an example of the hypocentral accuracy simulation results in the same manner as Figure 3. This indicates how much the hypocentral accuracy would improve if stations are added to the Kakkonda network. These figures contour the distribution of estimated errors in the Z coordinate of microearthquakes that occurred at the grid points. Additional stations result in an improvement in hypocentral accuracy, that is, a reduction in the uncertainty in the Z coordinate.

As these results imply, we can check hypocentral accuracy using an imaginary network of stations, before installation, by this simulation method. It is also possible to consider the reliability of hypocenter locations when we correlate fracture systems etc., with the distribution of microearthquakes observed by the network. We also found that the hypocentral accuracy simulation is very useful in examining and designing the arrangement of stations, the number of stations, the accuracy of picking P- and S-waves and the accuracy of station coordinates to attain the requisite hypocentral accuracy by taking the budget into account.

7. SENSITIVITY STUDY OF PARAMETERS OF THE DETECTABILITY AND HYPOCENTRAL ACCURACY SIMULATIONS

We conducted sensitivity studies on how parameters of simulation influence detectability and hypocentral accuracy in order to obtain information for guidelines in designing a network of stations. The sensitivity study was conducted for the following cases: changing the number of stations, changing the location of stations and changing parameters (errors of picking P- and S-wave initial phases, errors of velocity structure, errors of station coordinates) with respect to the basic parameters.

7.1 Result of the sensitivity study on parameters of the detectability simulation

We examined detectability, the minimum magnitude of detectable earthquakes, by changing trigger levels that depend on the ground noise levels, between 1×10^{-7} and 2×10^{-6}m/s (Figure 5). Figure 5 shows the variety of detectability at three points: the center of the network of stations (near station KM-5, 1km below sea level), the edge of the network (near station KM-1, 1km below sea level) and outside the network (about 1.5km outside KM-1, 1km below sea level). Detectability within the network is much better than outside the network. When trigger levels become small, the magnitude of detectable earthquakes decreases logarithmically. Since average noise levels in the Kakkonda field are 1×10^{-7} to 5×10^{-7}m/s and trigger levels are 5×10^{-7} to 3×10^{-6}m/s, it is expected from the result that microearthquakes up to magnitude -1 are detectable within the Kakkonda network. Figure 6, showing the frequency distribution of microearthquake magnitudes observed in the Kakkonda field during 1995, suggests that the expected detectability of the Kakkonda network is greater than magnitude -1. Thus the result of the sensitivity study matches field observations indicating that the detectability simulation results are reliable.

7.2 Result of the sensitivity study on parameters of the hypocentral accuracy simulation

We examined the influence of parameters to hypocentral accuracy, changing parameters, errors of picking P-wave, errors of station coordinates, errors of velocity model and the number of stations where the initial motion of P-waves can be picked. In the following results we show the value of the position just under station KM-5, 1km below sea level, as representative.

Figure 7 shows the correlation between errors of picking P-waves and errors of hypocenter coordinates; figure 8 the relationship between errors of station coordinates and errors of hypocentral coordinates; figure 9 the relationship between errors of the velocity model and errors of hypocentral coordinates; and figure 10 the relationship between the number of stations where the initial arrival time of the P-wave can be picked and errors of hypocentral coordinates. Error factors in picking P-waves were changed between the sampling period (0.001sec) and the basic error of picking S-waves (0.02sec). Errors of station coordinates were changed between 0.001 and 0.1km. P- and S-wave velocity errors were varied between 0 and 0.5km/s and errors of thickness of velocity layers were fixed at 0.1km. The number of stations was changed to 4, 7, 10, 15, 20 and 25 stations. We utilized 25 stations for microearthquake monitoring in the Kakkonda field with 10 stations permanent and another 15 temporal.

From the sensitivity study of parameters of hypocentral accuracy, we found the following relationships between the parameters and hypocentral accuracy. Estimated errors for the Z coordinate of a hypocenter are the largest while errors for the Y coordinate are bigger than that of the X coordinate when the values of the parameters are equal. These characteristics result from the horizontal distribution of stations near surface and the wide distribution along the X (west to east) direction. For better horizontal accuracy, stations should be distributed evenly. Estimated errors of the hypocenter coordinates increase if errors of picking P-waves, errors of station coordinates and errors of the velocity model increase or if the number of stations decrease. A comparison of the results (Figures 7 to 10) show that errors of the velocity model is most harmful to hypocentral accuracy. Observations using many temporal stations is effective in analyzing three dimensional velocity structures. If errors of the velocity model become smaller as a result of the three dimensional velocity analysis, hypocentral accuracy will also become better.

7.3 Summary of the sensitivity study

The results of the sensitivity study of parameters of the detectability and hypocentral accuracy simulations indicate that the following factors should be taken into account in designing a network of seismic stations.

<u>Results of the sensitivity study for the detectability simulation</u>

- The nearer hypocenter locations are to the stations, the smaller the magnitudes of detectable earthquakes become. Stations should be placed near the seismic zone.
- The wider the distribution of stations, the greater the extent of the detectable zone. Stations should be distributed so as to cover the seismically active zone.
- The more densely the stations are distributed, the more improved is the detectability. Thus, as many stations as possible should be installed.
- Detectability along the vertical direction improves when the station is placed in a deep observation borehole. Some stations should be located deep in the ground.
- Detectability becomes better if trigger levels are reduced by noise level reduction. A seismometer should be installed at the bottom of a deep borehole to reduce the effect of ground noise in places where it is strong. Noise levels in the borehole at 100m depth becomes 1/10 the noise level at the surface (Yamamizu *et al*, 1977).

<u>Results of the sensitivity study for the hypocentral accuracy simulation</u>

- The nearer the hypocenter is located to the station, the greater the observation accuracy becomes. Stations should be placed near the seismic zone.
- The farther away the hypocenters are from the network of

stations, the lower the observation accuracy becomes. Stations should be distributed widely to cover the seismic zone.

- The more densely the stations are distributed, the better the observation accuracy becomes. As many stations as possible should be installed. However, since hypocentral accuracy does not increase linearly with an increase in the number of stations, the number of stations should be examined by conducting the hypocentral accuracy simulation.
- Hypocentral accuracy is improved with improvement in the accuracy of picking P- and S-waves. Ground noise levels can be decreased by setting the seismometer under the ground. Picking accuracy can be improved by increasing the sampling frequency.
- The smaller the errors are in locating station coordinates, the better the hypocentral accuracy becomes.
- Errors of the station Z coordinates (elevation) affect the hypocentral accuracy more than errors of the X or Y coordinates (horizontal axes). Therefore, stations should be precisely located, especially the Z coordinate.
- The less the errors of the velocity model are, the better the hypocentral accuracy becomes. A more precise velocity model can be attained by considering geological information and the results of sonic logging and by conducting velocity model exploration methods such as refraction and reflection surveys and velocity structure inversion analyses.
- When a station is sited in a deep observation borehole, the hypocentral accuracy along the vertical direction improves. Some stations should be placed at depth.

8. GUIDELINES IN DESIGNING A NETWORK OF STATIONS BASED ON THE RESULTS OF THE SENSITIVITY STUDY

Considering the objective of detectability and hypocentral accuracy to detect changes in the reservoir conditions, which we set in the previous sections, the results of the sensitivity study led to the following guidelines for designing a network of stations: make noise levels less than 5×10^{-7} and trigger levels less than 1×10^{-6}; set sampling speed at more than 100Hz and make picking accuracy less than 0.01sec; improve errors of velocity to less than 0.2km/sec and errors of layer thickness of velocity model to less than 0.1km by velocity structure exploration (e.g., refraction survey, sonic logging etc.); survey seismic station locations precisely and make the margin of error in locating station coordinates less than 0.01km; and install more than seven permanent stations.

In this study, we could confirm that the Kakkonda network satisfies these guidelines and has enough detectability and hypocentral accuracy for a permanent network. However, for three dimensional velocity structure analysis, more than ten stations should be installed to get precise results.

9. CONCLUSION

In order to set the guidelines in designing a network of stations which can detect geothermal reservoir time-lapse changes, we conducted detectability and hypocentral accuracy simulations in the Kakkonda network of stations. As a result,
it was proved that the detectability and hypocentral accuracy simulations are very effective in verifying if a network of stations could attain the intended degree of detectability and hypocentral accuracy before seismometers are installed. We also established general guidelines in designing a network of seismic stations. When we design a network of stations to detect reservoir condition changes, it is very important consider results obtained in this study and to conduct the detectability and hypocentral accuracy simulations.

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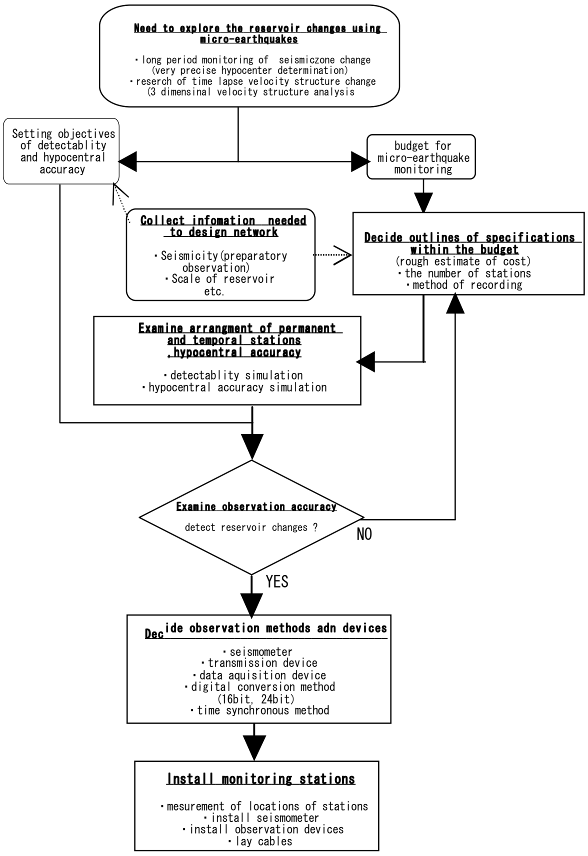


Figure 1. Flow chart of designing permanent and temporal network of stations

Table 1. Basic parameters for sensitivity study in the Kakkonda field.

(a) parameters about observation

Station	Parameters of detectability simulation		Parementers of hypocentral accuracy simulation				
	trigger condition	Trigger level	Error of picking		Error of coordinates		
	3AND	Amplitude	P-wave	S-wave	X	Y	Z
	--	$x10^{-7}$m/sec	sec	sec	km	km	km
KM-1	on	5	0.005	0.02	0.01	0.01	0.01
KM-2	on	5	0.005	0.02	0.01	0.01	0.01
KM-3	on	5	0.005	0.02	0.01	0.01	0.01
KM-4	on	5	0.005	0.02	0.01	0.01	0.01
KM-5	on	20	0.005	0.02	0.01	0.01	0.01
KM-6	on	10	0.005	0.02	0.01	0.01	0.01
KM-7	on	10	0.005	0.02	0.01	0.01	0.01
KM-8	on	20	0.005	0.02	0.01	0.01	0.01
KM-9	on	5	0.005	0.02	0.01	0.01	0.01
KM-10	on	5	0.005	0.02	0.01	0.01	0.01

(b) Parameters of velocity model

Parameters of hypocentral accuracy simulation						
Layer	Depth			Error of velocity model		
				P-wave	S-wave	Thickness
	Meters			km/s	km/s	km
1	3000	-	628	0	0	0
2	628	-	242	0	0	0
3	242	-	-262	0	0	0
4	-262	–	-723	0	0	0
5	-723	–	-2440	0	0	0
6	-2440	–	-10000	0	0	0

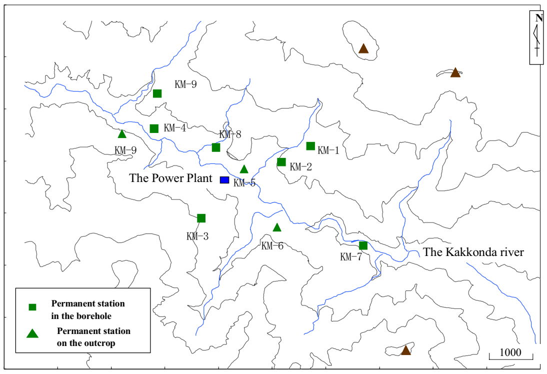
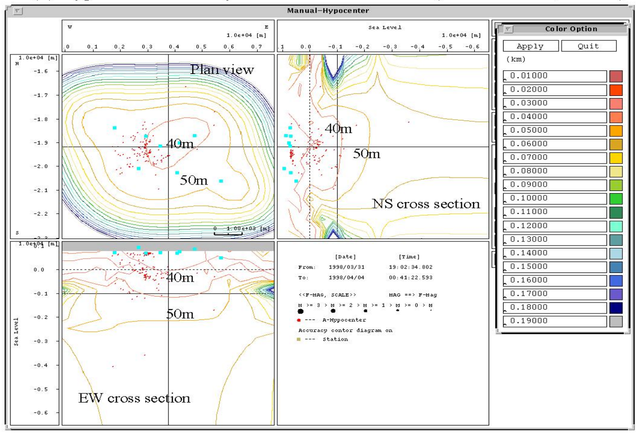
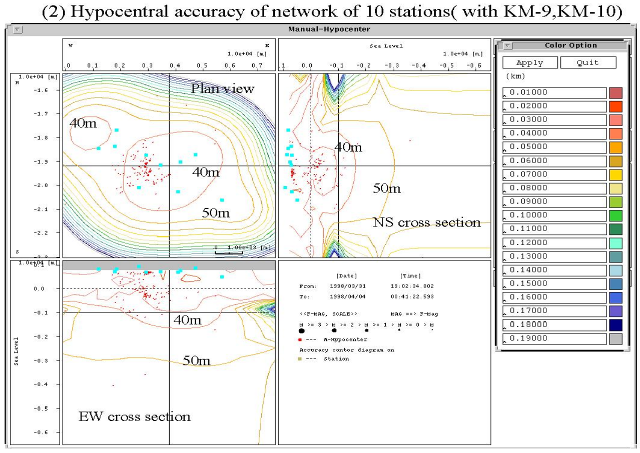


Figure 2. Locations of seismic stations.

(1) Hypocentral accuracy of netwok of 8 stations (without KM-9,KM-10)



(2) Hypocentral accuracy of network of 10 stations(with KM-9,KM-10)



(3) Hypocentral accuracy of network of 11 stations(with another station behind P.S.)

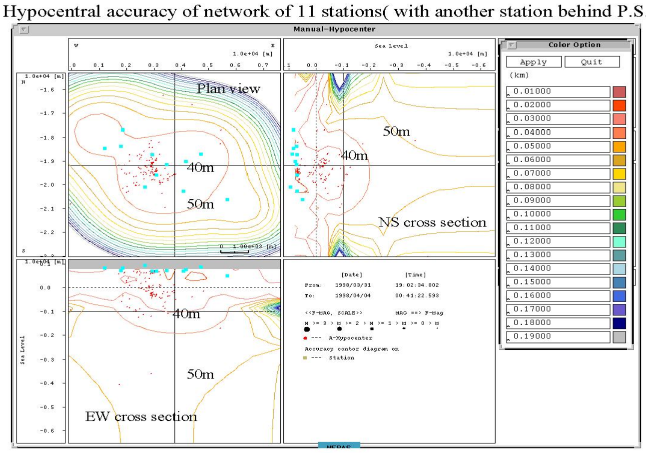


Figure 3. Results of the detectability simulation in the Kakkonda field. P.S.= Power station

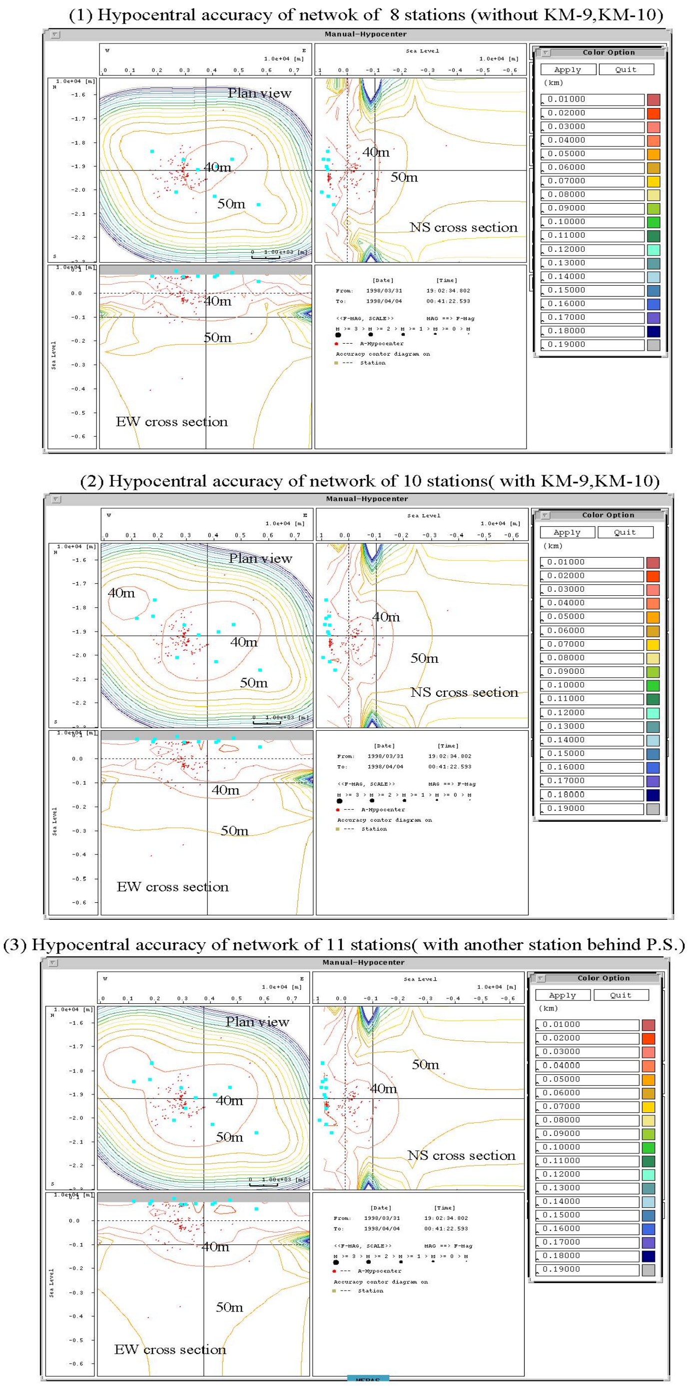


Figure 4. Results of the hypocentral accuracy simulation in the Kakkonda field (the Z coordinate error).

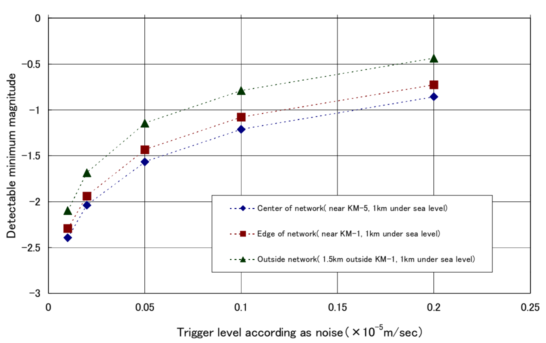


Figure 5. Correlation between trigger levels and detectability in the Kakkonda field.

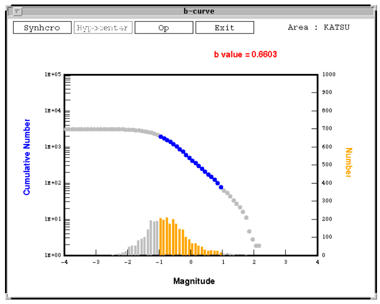


Figure 6. Frequency distribution of magnitudes of micro-earthquakes observed in 1995 in the Kakkonda field.

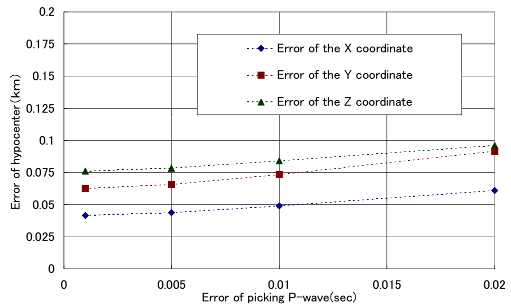


Figure 7. Correlation between errors of picking P-waves and errors of hypocentral coordinates in the Kakkonda field

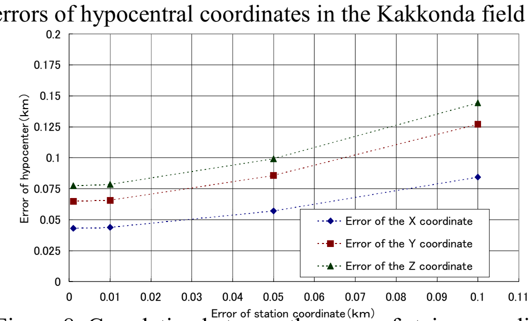


Figure 8. Correlation between the erors of staion coordinates and errors of hypocentral coordinates in the Kakkonda field.

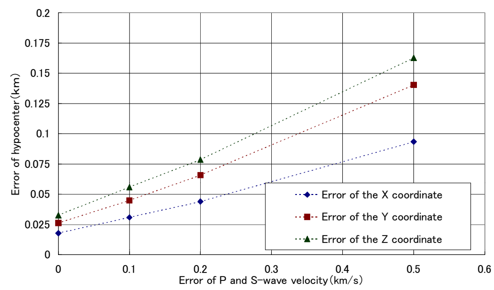


Figure 9. Correlation between errors of velocity model and errors of hypocenter coordinates in the Kakkonda field.

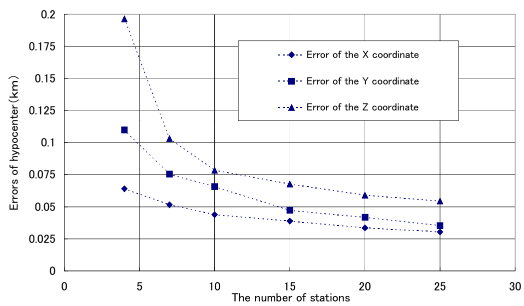


Figure 10. Correlation between the number of stations and the errors of hypocenter coordinates in the Kakkonda field.