DEVELOPMENT OF A TECHNOLOGY TO EXPLORE GEOTHERMAL RESOURCES BY MEASURING CHANGES IN MICRO-EARTHQUAKES

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SUMMARY - Many micro-earthquakes occur in geothermal fields when geothermal fluid is withdrawn from or re-injected into geothermal reservoirs. It is possible to delineate a geothermal reservoir and the flow path of geothermal fluid through precise research on the hypocenter distribution of micro-earthquakes. Technology for optimizing the design of micro-earthquake monitoring network systems, a software for micro-earthquake data processing and analysis, and three-dimensional seismic velocity analysis technique are being studied.

1. INTRODUCTION

Minimizing the decrease in power generating output and increasing overall power generating output, are both very important tasks for geothermal energy development. Therefore, technology for identifying the physical and hydrological changes such as pressure, temperature and fluid phase transition, is required. Such changes occur when geothermal fluid is withdrawn from or re-injected into geothermal reservoirs and affect micro-earthquake distribution and seismic velocity structure.

In the Geysers, California, United States, Foulger et al.(1997) conducted Vp/Vs tomographic inversion using micro-earthquake data of 1991 and 1994 separately and detected the change of Vp/Vs in the reservoir. In the Kakkonda geothermal field, Tosha et al. (1993) estimated the geothermal fluid flow paths utilize an expansion of the seismic zone. Therefore, micro-earthquakes are good indicators for the existence of fractures.

It is very important to detect as many small earthquakes as possible and to accurately determine hypocenters in order to detect the time-lapse changes of the geothermal reservoir condition. For this purpose, it is necessary to develop a technology for optimizing the design of micro-earthquake monitoring network systems and a technique to accurately identify the hypocenter. An accurate model of the seismic velocity structure is especially important to locate microearthquakes. Therefore, a technique for three-dimensional seismic velocity analysis is needed, which is specific for geothermal fields, because usually techniques are suitable for analyzing larger areas. Furthermore, software for micro-earthquake data processing and analysis, which can determine the hypocenter accurately and easily, is required so that micro-earthquake data in geothermal fields can be used.

New Energy and Industrial Technology Development Organization (NEDO) launched an R&D project "Development of Technology for Reservoir Mass and Heat Flow Characterization" in 1997 (Horikoshi, 1998). We are researching and developing the following techniques; a technology for optimizing the design of micro-earthquake monitoring network systems, software for micro-earthquake data processing and analysis (MEPAS), and a three-dimensional seismic velocity analysis technique.

2. TECHNOLOGY FOR OPTIMIZING THE DESIGN OF MICROEARTHQUAKE MONITORING NETWORK SYSTEMS

Technology development for optimizing the design of a micro-earthquake monitoring network system is needed to detect the time-lapse changes of micro-earthquake hypocenter distribution. Seismic monitoring networks should be able to detect micro-earthquakes and accurately locate their hypocenters. We are studying the optimum design of seismic network system through simulations.

2.1 A Flow for Seismic Network Design

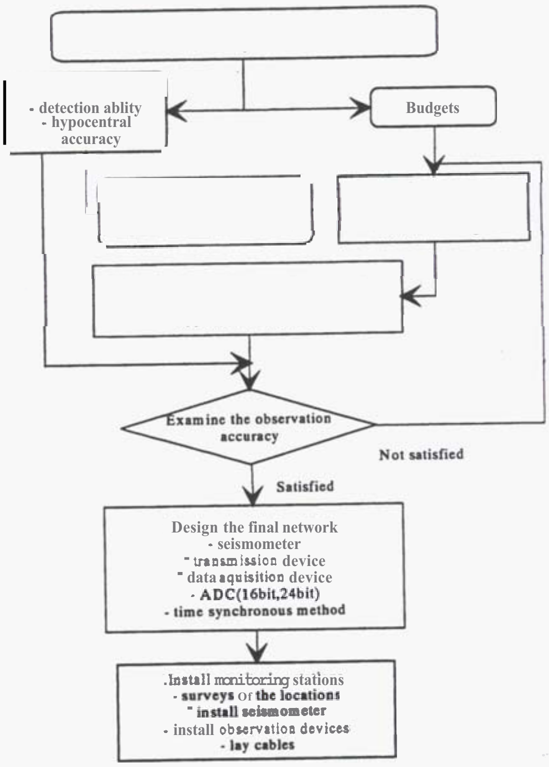

Figure 1 Flowchart of designing seismic monitoring network

(1) Set the objectives of detection ability and hypocenter accuracy to detect reservoir changes
(2) Decide an outline of specifications of the monitoring network which satisfies the budget for this project. At the beginning, take account of rough seismicity, volume of reservoir etc. Measure the ground noise or make a preliminary observation as necessary.
(3) According to the outline, design locations of stations and accuracy of observation. In this process, simulate detection ability and hypocenter accuracy. Then examine the arrangement of stations needed to monitor the change of the seismic zone for a long period to explore the time-lapse velocity structure.
(4) If the initial network of stations is found not to have enough observation accuracy fiom a result of the simulations, re-examine the specifications.
(5) If the accuracy of the network is sufficient, examine the method and equipment for monitoring within the limitations of the budget.

2.2 Detection Ability and Hypocenter Accuracy Simulation

The simulation of detection ability and hypocenter accuracy are very useful tools for seismic network design. The simulation are functions provided by the Micro-Earthquake Processing and Analyzing System (MEPAS) (Miyazaki et al., 1995).

Detection ability simulation can estimate the distribution of minimum magnitudes which can be recorded at a certain point. The minimum magnitudes are calculated by comparing the trigger levels (i.e. ground noise levels) of all stations and the trigger condition with the velocity amplitude that will be recorded at each station for the supposed hypocenter. Watanabe's (1971) equation is used for the estimation of the velocity amplitude for at each station. Minimum magnitudes are calculated at 20×20×20 grid points in the three dimensional target area.

Hypocenter accuracy simulation can estimate the distribution of errors of hypocenters. It is based on the analytical method of Peters and Crosson (1972).

2.3 The Detection Ability and the Hypocenter Accuracy Simulation for the Seismic Monitoring Network in the Kakkonda Geothermal Field

The seismic network in the Kakkonda geothermal field was examined through the detection ability simulation and hypocenter accuracy simulation. The seismic network in the Kakkonda field consists of ten stations (KM-1 to KM-IO). Seismic signals are recorded when the trigger conditions signal any 3 of 10 stations. Background noise ranges fiom 1×10^{-7} to 1×10^{-6}m/s (i.e. 10 to 100 micro-kine). A six horizontal-layered velocity model is used for hypocenter determination. Station coordinates are measured by the open traverse survey, therefore the errors of station coordinates are estimated to be less than a few meters.

Figure 2 shows an example of detection ability simulation results. These figures show the distribution of expected minimum magnitude of a supposed micro-earthquake which occurs at grid points and can be recorded by each seismic network as a contour diagram. The upper figure (1) consists of 8 stations and the lower figure (2) consists of 10 stations. This result indicates the improvement of detection ability as a result of adding stations before

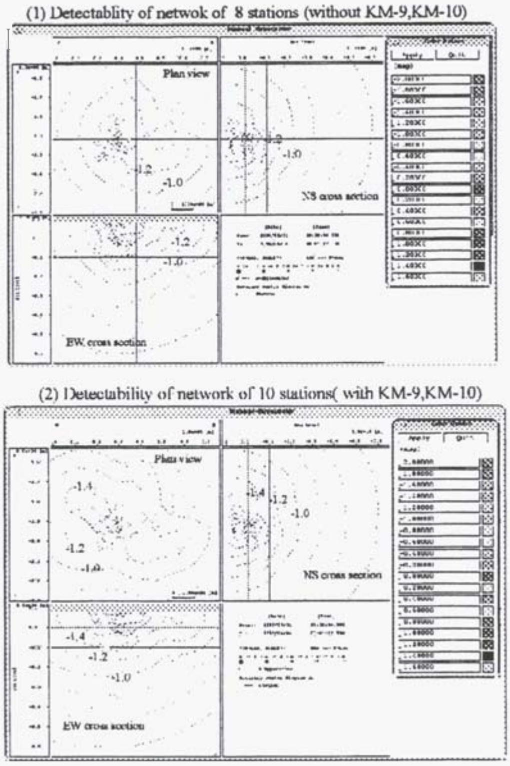

Figure 2 Result **of** the detection ability simulation in the Kakkonda geothermal field

installing the stations by the detection ability simulation. The detection ability of an imaginary network can be checked before installation. Thus, the detection ability simulation is very useful to examine and optimize the arrangement of stations, the trigger condition, the trigger level and the ground noise reduction to achieve detection, taking the budget into account.

Figure 3 shows an example of the hypocenter accuracy simulation results. These figures show the distribution of the estimated errors of the Z coordinate of earthquakes which occurred at grid points on the contour diagram. The upper figure (1) consists of 8 stations and the middle figure (2) consists of 10 stations. This result indicates the improvement of hypocenter location accuracy as a result of adding stations to the hypocenter accuracy simulation. It is also possible to consider the reliability of hypocenter locations of the micro-earthquakes observed by the real network. Thus, the hypocenter accuracy simulation is very useful to examine and design the arrangement of stations, the number of stations, to accurately pick P and S-waves, to find the accuracy of the station coordinates and to determine the accuracy of the velocity structure.

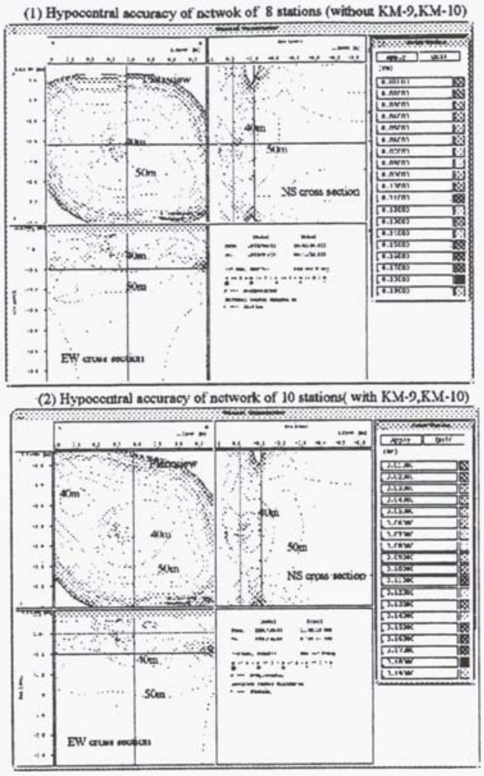

Figure 3 Result **of** the hypocenter accuracy simulation in the Kakkonda geothermal field (the Z coordinate error)

2.4 Sensitivity Study of Parameters of the Detection ability and the Hypocenter Accuracy Simulation

The guidelines for the design of a seismic network can be obtained through a sensitivity study of the detection parameters and the hypocenter accuracy simulation.

Figure **4** shows the detection ability at three positions, at the center of the network (near the station KM-5, 1km under sea level), at the edge of the network (near the station KM-1, 1km under sea level), and outside the network (about 1.5km outside KM-1, 1km under sea level).

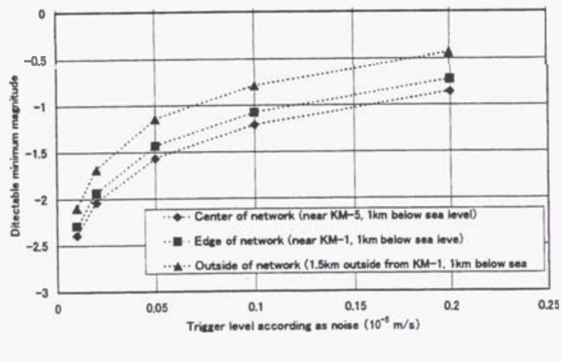

Figure 4 Relation between trigger levels according as noise levels and detection ability.

Detection ability in the network is much better than outside the network. If the ground noise level becomes small, the magnitude of detectable earthquake reduces as a log curve. Since the average noise levels of 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 fiom the result that micro-earthquakes up to magnitude -1 will be detectable inside the Kakkonda network. Indeed, the result of sensitivity study matches the result of observation in the Kakkonda geothermal field. Therefore, the detection ability simulation is reliable and can be used for designing a seismic network.

Figure 5 shows the relation between the number of stations where initial motion of P-waves can be picked and the errors in locating hypocenter coordinates. The number of stations fiom 4 to 25 stations. The errors in the hypocenter coordinates vary and depend on the number of stations. This shows that seismic monitoring with many temporal stations is effective for accurate hypocenter distribution.

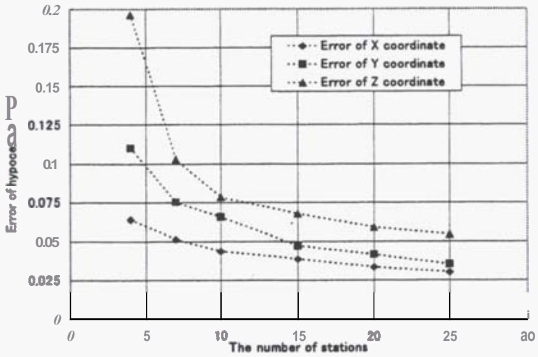

Figure 5 Relation between the number of stations which could detect initial motion of P-wave and the error of hypocenter.

Through the sensitivity study, the following information is suggested for the seismic network design.

(1) It is advisable that stations are placed near the seismic zone.

(2) It is advisable that stations are distributed to cover the seismically active zone.

(3) It is advisable that as many stations as possible are installed.

(4) Detection ability is improved by one deep station.

(5) Install the seismometer at the bottom of a deep borehole to decrease ground noise.

(6) Increase sampling frequency to improve picking accuracy.

(7) Station coordinates should be measured precisely so that the hypocenter can be determined more accurately.

(8) The precise velocity model, which is constructed from geological information, sonic logging, check shot and a velocity structure inversion analysis, should be used for hypocenter determination.

3. DEVELOPMENT OF A SOFTWARE FOR MICRO-EARTHQUAKE DATA PROCESSING AND ANALYSIS (MEPAS)

Hypocenter determination is the basic procedure for the exploration of the flow path of geothermal fluid and reservoir condition changes. Real-time processing of hypocenter determination is especially useful for tracing the hypocenter movement and detecting the reservoir changes during valve operation.

Micro-Earthquake data Processing and Analysis System (MEPAS) is a software designed for geothermal exploration, which was developed in NEDO's project (Miyazaki et al, 1995). In our project, some functions of MEPAS are reinforced, especially on the real time processing of hypocenter determination and the database modules. Furthermore, operating system of MEPAS will be fully converted fiom UNIX to Windows NT. These improvements can make MEPAS easier to use and can reduce the data processing workload and the cost.

3.1 The Operating System and Structure of MEPAS

Formerly, MEPAS was developed as a UNIX base application. In this project, MEPAS will be converted to Windows NT.

Table 1 Operating environments of both former and new MEPAS

Hardware	Personal Computer(PC/AT)
Operating System	Windows NT Workstation 4.0
Program Languages	Visual Basic 5.0, Visual C++ (Display part)
	FORTRAN77 (Processing part)
Database	Oracle8
Graphic Library	OpenGL

The operating environments of both the former and the new MEPAS are shown in Table 1. The user interface of Windows NT is popular. Furthermore it is good for continuous and long operation. We will adopt Oracle8 as the database management system of MEPAS and "win" format (Urabe and Tsukada, 1992) as the wave data format.

The structure of MEPAS is shown in Figure 6. MEPAS is divided into two subsystems, the Real Time Processing System by the name of MEPAS-R and the Off-line Fully Functional Processing System by the name of MEPAS-F.

The Real Time Processing System is an additional function in the current project. This system can report the hypocenter and magnitude to the staff of a geothermal power plant in real time automatically. The Off-line Fully Functional Processing System consists of both manual and automatic processing functions. Using these functions, a user can easily analyze micro-earthquake data. A database function links these two systems so that the user may manage MEPAS-R/F data with ease.

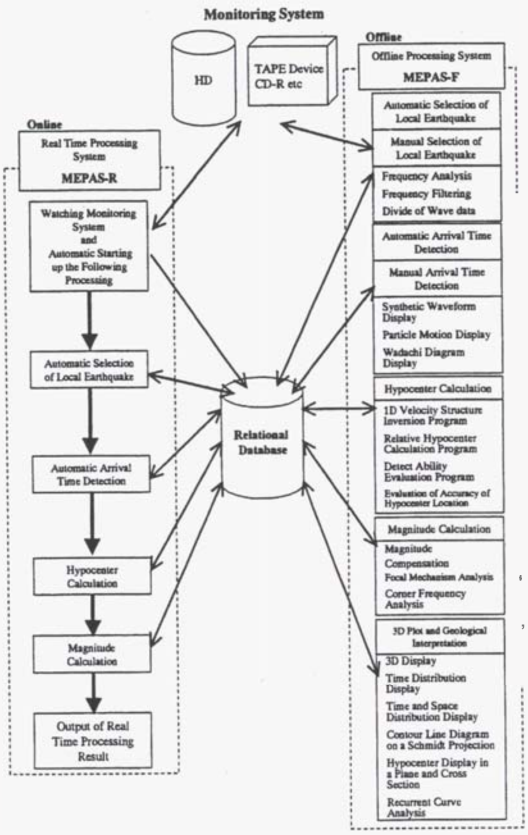

Figure 6 The structure of MEPAS

3.2 Real Time Processing System

A time chart of the real time processing system of MEPAS-R is also shown in Figure 7. MEPAS-R works independently with the monitoring system. MEPAS-R monitors the contents the PC's Hard Disk at regular intervals. When new micro-earthquake data are recorded in the PC's Hard Disk, MEPAS-R copies the micro-earthquake data fiom the PC's Hard Disk to another PC, it then starts processing. In this case, micro-earthquake monitoring is not stopped by faults in MEPAS-R, because the analyzing PC is independent fiom the monitoring PC.

3.3 Off-line Processing System

MEPAS-F consists of some manual processing functions, for example, Manual Selection of local earthquakes, and Manual Arrival time detection. This system has automatic processing functions. For example, a user can display waveforms with the results of automatic arrival time detection, and modify the arrival times manually. Users can analyze the micro-earthquake data in detail for the purpose of exploring geothermal reservoir, they can use the 3D plot and make a geological interpretation (Figure 8).

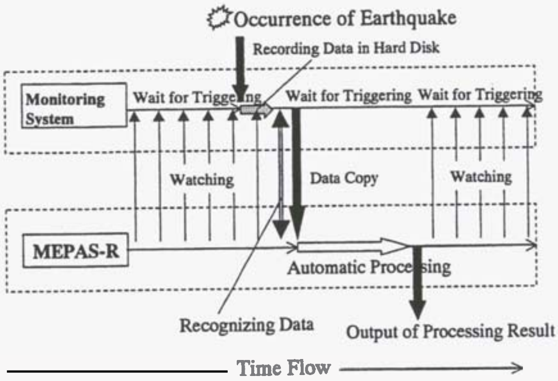

Figure 7 A time chart of real time processing system of MEPAS-R

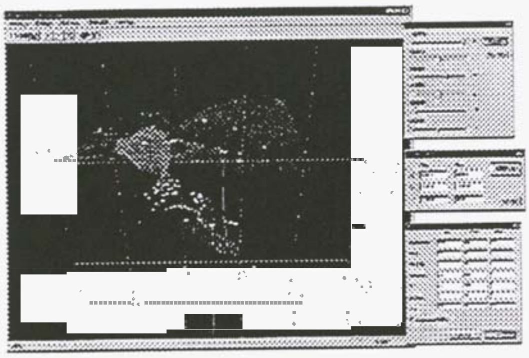

Figure 8 An example of 3D display.

4. DEVELOPMENT OF A THREE DIMENSIONAL SEISMIC VELOCITY ANALYSIS TECHNIQUE

The technique for accurate three-dimensional seismic velocity analysis is required to detect changes in the reservoir and the seismic velocity structure. The technique is useful to accurately determine hypocenters in heterogeneous geothermal reservoirs. The technique for three-dimensional seismic velocity analysis is studied in this project, which is required for geothermal project because the usual techniques are only suitable for analyzing a wide area.

The simultaneous inversion programs of 3-D velocity and hypocenter, Thurber (1983) and Zhao et al. (1992) are investigated. Both techniques were originally developed for analyzing wide seismic velocity structure. Therefore, we will select a technique which is more suitable for geothermal reservoirs.

5. CONCLUSIONS

A general guideline for the design of a micro-earthquake network system which can detect time-lapse changes in reservoir conditions, was suggested through the detection ability simulation and the hypocenter accuracy simulation of the Kakkonda network. In the study, the detection ability and the hypocenter accuracy simulations appear very effective to check if the network can attain detection ability and hypocenter accuracy before seismometers are installed.

Some functions of **MEPAS** such as real time processing of hypocenter determination and a data base, were designed. A preliminary program code was developed. The automatic processing of sorting seismic wave arrival time detection and hypocenter determination were improved and are faster. Program codes of the applied analysis parts of MEPAS, e.g. 3D compound display of a hypocenter and a geological information which runs on UNIX, were converted to a Windows NT Workstation. The user interfaces were also improved to make them more user-friendly.

Some algorithms for three dimensional seismic velocity analysis were examined. As a result, two techniques for three-dimensional seismic velocity analysis are available. One of a techniques will be selected and improved in this project.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Foulger, G. R., Grant C. C., Ross, A. (1997). Industrially induced changes in Earth structure at The Geysers geothermal area, California, Geophys. Res. Lett., 24, 135-137.

Horikoshi, T., Nagahama, N and Okubo, Y. (1998). Reservoir Mass and Heat Flow Characterization. GRC Trans., vol22, 165-169.

Miyazaki, S., Hanano, M., Kondoh, T., Yoshizawa, H., Kajiwara, T., Tsuchibuchi, S., Takahashi, M., Muraoka, H., Nagano, S. and Mitsuzuka, T. (1995). Micro-earthquakes data processing and analysis system(MEPAS), a software for geothermal applications, Proc. WGC 1995, Florence, Italy, 3023-3028.

Peters, D. C. and Crosson, R. S. (1972). Application of prediction analysis to hypocenter determination using a local array, Bull. Seism. Soc. Am. ,62,775-788.

Tosha, T., Sugihara, M., Nishi, Y. (1993). Micro-earthquake activity at the Kakkonda geothermal field in Japan, Proc. 15th NZ Geothermal Workshop 1993,175-179.

Thurber, C. H. (1983). Earthquake locations and three-dimensional crustal structure in the Coyote Lake area, central California., J. Geophys. Res., 88, 8226-8236.

Urabe,T. and Tsukada,S. (1992). win – A Workstation Program for Processing Waveform Data from Microearthquake Networks. Programme and Abstracts, the Seismological Society of Japan, 1992, No.2, 331. (in Japanese)

Watanabe, A. (1971). Magnitude of the near earthquake, Jisin, 24, 189-200(in Japanese with English abstract).

Zhao, D., Hasegawa A. and Horiuchi S. (1992). Tomographic imaging of P and S wave velocity structure beneath Northeastern Japan., J. Geophys. Res., 97, 19909-19928.