IAEA-TECDOC-343

APPLICATION OF MICROEARTHQUAKE SURVEYS IN NUCLEAR POWER PLANT SITING

A TECHNICAL DOCUMENT ISSUED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1985

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Printed by the IAEA in Austria
June 1985

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FOREWORD

In the siting of nuclear power plants the adequacy of seismological data base is often questioned. Installation and operation of a microearthquake network around a site can provide further insight into the seismicity of the site and assist in the related siting decisions.

With the new development in instrumentation and record processing microearthquake surveys have been increasingly applied in the siting of important facilities and, in particular, in the siting of nuclear power plants for obtaining background seismicity information when this is not readily available as well as for identification of suspect geological features in the site vicinity.

The effort involved in the application of a microearthquake survey is relatively small when compared to the whole siting process for a nuclear power plant and can give important results in a relatively short period of time.

This Technical Document is intended for use by both utilities that are actively involved in the nuclear power plant siting process and the regulatory bodies who may wish clarification of certain aspects of the safety studies related to siting. The documents provides information on both practical and technical aspects of the use of microearthquake surveys in nuclear power plant siting as well as addressing issues which are necessary in the decision making process of planning a site investigation. For this reason the capabilities of microearthquake surveys are cited along with their limitations.

It is important to note that better instrumentation and record processing together with the tendency of nuclear power plant construction in developing countries where, in general, both seismicity data and geological studies are scarce, greatly enhance the role of microearthquake surveys in nuclear power plant site investigations. Finally the results of microearthquake surveys will be useful when they are interpreted by experienced geologists, seismologists and engineers, in combination with geological studies and macroseismic data.

ABSTRACT

After an overview of the use of microearthuake survey in decisions related to the siting of nuclear power plants, the main aspects of a microearthquake survey network are discussed. The use of microearthquake surveys in investigating problems related to near-field (floating) earthquakes is also discussed. The discussion is centered on the practical application of such a survey leading from objectives and limitations over to planning, instrumentation, operation, maintenance, processing of the data, and interpretation and reporting of the results. An appendix entitled Earthquake Magnitude gives useful background information for definitions of different types of magnitude and their calculation using the records from microearthquake surveys.

CONTENTS

1. INTRODUCTION

The seismological evidence of past specific earthquakes is based on those accumulated by man which includes both historical and instrumental data. Historically observed data are information collected on the damage generated by the old earthquakes. Instrumental data, are the data recorded by instruments installed in a region. For some countries sufficient historical and instrumental data are already available. However in many other countries the historical and instrumental data are very scarce. In such a case microearthquake surveys are a beneficial way in which to integrate the limited inventory of seismological information that may be available for a given region.

Earthquakes of magnitude less than 3 are generally referred to as microearthquakes. Recordings of microearthquakes permit drawing inferences on the seismicity of the region, location of active structures, properties of earthquake source zones, confirmation or questioning of the rate of historical seismic activity and possibly, evaluation of the attenuation characteristics of the site region, thus providing valuable information for future estimation of the seismic hazard.

In the siting of nuclear power plants the adequacy of the seismological data base is often questioned. As discussed in the Agency's Safety Series No. 50-SG-S1 "Earthquakes and Associated Topics in Relation to Nuclear Power Plant Siting", the use of microearthquake data may be one excellent and powerful tool in providing further insight into the siting decisions related to seismicity for a nuclear power plant. Microearthquake networks are currently operated routinely throughout the world. The relatively small effort required for the application of a microearthquake survey can provide further assurance of the actual seismic situation in the site region. Therefore, a microearthquake survey can be an important component of studies and investigations of the seismic aspects of nuclear power plant sites, especially to those directed at determining, to the best extent possible, the accurate locations of potentially active structures and the further treatment of earthquakes which have not been associated with known structure (the floating earthquakes) and its appropriate ground motion parameters.

Information on microearthquakes in a region can be acquired through the installation and careful operation of a microearthquake network. However, the use of microearthquake data to estimate or predict larger magnitude events is still an evolving science. It is advised, therefore, that the microearthquake survey data would not be used as a direct extrapolation to make a magnitude determination for the design basis ground motion at a site. Instead, it is recommended that the continued acquisition of microearthquake survey data be utilized in conjunction with other available geological and seismological data to provide further confirmation of the siting decisions which are being reached.

This report relies on the guidance provided in the IAEA Safety Series No. 50-SG-S1 for evaluation of the design basis ground motion at a site and the guidance provided in Lee and Stewart [1] for the development and installation of a microearthquake survey network. In particular, the list of definitions in the former document should be consulted.

The purpose of this report is to provide general information on the usefulness of a microearthquake survey in conjunction with nuclear power plant siting, as well as an awareness of the major items that need to be addressed and the need for judicious use of information obtained from a microearthquake survey in the evaluation of the design basis ground motion at a site.

1.1 Nuclear Power Plant Design Basis Ground Motion Evaluation

The evaluation of design basis ground motion consists of the following steps:

- Identification of seismically active structures in the region of the site;
- Evaluation of the maximum earthquake potential in each of these structures;
- Evaluation of the attenuation of the earthquake ground motion from the earthquake source to the site.
- Evaluation of the ground motion at the site.

1.1.1 Identification of seismically active structures

One use of a microearthquake survey is to determine the locations of microearthquakes and, in certain cases, to evaluate the fault plane solutions. If the seismotectonic structures (i.e. earthquake source zone) are not in a quiescent period and the number of microearthquakes located is sufficiently large, it is possible to identify the microearthquake distribution and geometry of the fault plane. These in turn may point out particular seismotectonic structures, confirm their activity and give an indication of their characteristics.

1.1.2 Evaluation of maximum potential earthquake

The rate of occurrence and magnitude of microearthquakes in the structures may be interpreted using the Gutenberg-Richter magnitude - frequency relationships. This may give at least an idea of the recurring time of a macroearthquake of a given severity - if it can be assumed that the earthquake occurrence rate in the region is constant and if the result with this method corresponds with that derived from the macroearthquake catalogue study. This may be a possible way of obtaining a rough estimation for checking the severity of the design basis ground motion evaluated by other means.

The recurring time for a macroearthquake of a given severity obtained by extrapolating a magnitude-frequency curve derived only with microearthquake data cannot be used for design without confirmation of the value by other means (for instance magnitude-frequency curve evaluation with instrumental and historical data). In fact, the rate of microearthquake generation may change with time. It should also be taken into account that at very high magnitude, the Gutenberg - Richter frequency curve is non-linear. This may not allow for the evaluation of the maximum earthquake potential from the curve. Moreover, the extrapolation error and those due to change in the rate of generation of microearthquake can be considerable.

1.1.3 Attenuation relationship

From the level of signals recorded by different stations in the network for relatively large microearthquakes, additional insight can be gained into developing or modifying an attenuation relationship for the site region. This information should be combined, whenever possible with the available strong motion data base to establish or modify the attenuation relationship to be used for the region.

1.2 Other Possible Contributions of the Microearthquake Network

Another possible application of microearthquake surveys is where they reveal lack of seismic activity. This is a definite positive result for the evaluation of a site for a nuclear power plant. Caution is required, however, in inferring that no seismicity is possible for this area based on the limited time of monitoring.

2. GENERAL OBJECTIVES OF MICROEARTHQUAKE SURVEYS IN RELATION TO NUCLEAR POWER PLANT SITING – DESIGN CONSIDERATIONS

The results obtained from a microearthquake survey can make the following contributions in evaluating the design basis ground motion for a site:

- Identification of the location of a fault without surface expression near the site;
- Contribution for reaching decisions regarding whether or not a known fault is active;
- Identification of activity related to other geological features (salt domes, diapirism, etc.);
- Identification of induced seismicity, i.e. determination of abrupt change of rate of earthquake occurrence due to reservoir impoundment or hydrocarbon extraction and injection from nearby deposits;
- Determination of general background seismicity in seismotectonic region of the site to help to correlate structures with earthquakes.

Since a microearthquake survey can be used to clarify the above issues, its installation and operation can assist in dealing with the problems of the consideration of both the floating and structure-associated earthquakes for design purposes. For the purposes herein, the floating earthquake is that earthquake which has not been associated with a specific tectonic structure or group of structure and must therefore be considered to occur near the site (IAEA Safety Series No. 50-SG-S1 sub-section 3.3.7.2).

The problem of the floating earthquake in the site vicinity is generally due to insufficient information regarding less prominent structures in the region. In such situations a nearfield design response spectrum associated with this floating earthquake is used for checking purposes alongside the standard type response spectrum such as that given in Appendix B of Safety Series 50-SG-S1. However, if all the earthquakes within the seismotectonic province of the site can be associated with tectonic structures, then the problem of the floating earthquake (and near-field design response spectrum) would be eliminated. The elimination of the near-field event would save considerable time and effort in the design and checking process. An efficient way to identify these less prominent, but possibly seismogenic structures is through a microearthquake survey in the site vicinity.

As in the case of most areas of seismic design, considerable judgment must be used in applying the survey to a better determination of how the floating earthquake problem should be treated. Although three years of monitoring may be adequate to assist in making such a judgement, longer terms of monitoring would be appropriate, especially in the case where the historical seismic record is inadequate. It is important to stress that the survey data be used on a case by case basis to make an assessment of the appropriate floating earthquake.

Basically, a microearthquake can assist greatly in determining whether or not a seismically active trend/zone exists in the region, and whether geologically-known faults and/or lineaments are generating earthquakes. To obtain meaningful results the microearthquake survey should be conducted over a period of at least three years and preferably much longer if at all possible*.

If the microearthquake survey gives negative results, i.e. only a few scattered microearthquakes are located, experienced seismologists and geologists, based on their analysis of this information along with the previously existing earthquake data (instrumental and historical), and tectonic and geophysical information, should be able to reach the conclusion that there is a very low probability that the design basis ground motion will occur directly at the site. In such a case, there may not be a need for special consideration or modification of standard design response spectra or site dependent response spectra due to the occurrence of the event in the immediate proximity of the site. It should be noted, however, that existing design spectra do already contain some high frequency content unless there are very special site conditions.

If a microearthquake survey does show some localized activity, the results can be used to provide a more specific definition of the design spectra for the site. The information acquired would be extremely valuable in determining the precise distance of the structure from the site and the distance at which the earthquake should be considered. This in turn, could be used to develop site dependent design response spectra appropriately modified to contain sufficient energy in the frequency range depending on the size of the structure and its distance from the site. Depending on the size of the structure, an earthquake of greater size may need to be considered.

In the case of poorly located historical seismicity, i.e. events located based on felt reports, microearthquake survey can also be of great assistance in reasonably associating such events with specific structures. For example, if there are a number of poorly constrained events in an area or region, and the survey can demonstrate the location of a seismically active structure within a reasonable distance of such events and the structure is determined to be large enough to generate an earthquake of the size observed; these events can often be associated with that structure. However, it should be pointed out that even with the best data all historical events can often not be unequivocally associated with a specific structure.

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* Microearthquake observation network may be continued, if possible, during the operation of nuclear power plants after its role for the siting purpose is completed. The microearthquake observation near the nuclear power plant can be very useful for providing seismological data for the earthquake engineering and prediction research.

A microearthquake survey can also be useful in determining the location of earthquakes that have occurred near a site. In particular, the results of a microearthquake survey can be used to delineate the precise location of the subducting zone, which would be very useful in seismic design considerations. Data from a microearthquake survey is also important in determining the rate of activity as well as assisting in delineating shallower structures in the site vicinity or region which may or may not be related to the subductions zones. Such information is used in reaching design decisions in areas of active subduction zones.

3. MICROEARTHQUAKE SURVEY

The results of a microearthquake survey depend on the characteristics and the number of the instruments installed, the procedure for the analysis, the site complexity, logistics, and their interpretation and integration with other available geological data.

3.1 Specific Objectives

3.1.1 Detection of microearthquakes

Microearthquakes are not generally felt by man. They can however, be detected by microearthquake observation stations. Since these stations also record man-made cultural noise and natural microseisms, three or more microearthquake stations separated by about 15 - 20 km are operated together to discriminate microearthquakes from other sources of seismic noise by their locations. It is generally possible to discriminate explosions, rock bursts and quarry blasts, from microearthquakes if the locations of quarrying, mining, and local civil construction projects are identified. However, some blasts may still go unidentified.

3.1.2 Location of microearthquakes

Determining the location parameters of a microearthquake i.e. the latitude and the longitude of the epicentre, the focal depth and the origin time, requires a minimum of four microearthquake recorders suitably located and operated on a common time base provided that, the regional velocity structure is known. To cover a typical region measuring 30 km x 30 km, eight microearthquake stations are recommended (see sub-section 4.3). In most cases, it should be possible to determine epicentres within ±1.0 km., focal depths within ±5 km, origin time with ±0.5 s for the microearthquakes occurring well within the network, the error in determining the arrival time of the first seismic phase could be within ±50 ms. After the operation of the network for some time, higher location accuracy, say ±0.2 km horizontally (in co-ordinates), ±1 km vertically and ±0.1 s in origin time, could be obtained by careful study. A good knowledge of the regional velocity structure is particularly essential for an accurate determination of the focal depth and the origin time.

3.1.3 Determination of crustal velocity structure

The main information resulting from a microearthquake survey, is the determination of the first P-wave arrival time. This information, for every microearthquake, contributes in determining the velocity structure. Initially a simple velocity structure is used for a preliminary location of microearthquakes. Later, through an iterative process the velocity structure is modified to improve the focal parameters and reduce their standard errors [2].

3.1.4 Evaluation of microearthquake magnitude

Earthquake magnitude is, to some extent, a measure of the size of the earthquake source. Microearthquake surveys in a region would enable to develop part of a magnitude scale for earthquakes in that region (see sub-section 7.6.4). It is then possible to estimate the magnitudes of future earthquakes relatively easily and accurately. Accurate determination of magnitudes is necessary in establishing the frequency-magnitude relationship (see sub-section 3.1.9) and in investigating the energy release as a function of space and time.

3.1.5 Identification of seismotectonic stuctures

A microearthquake survey conducted in areas where geological faults are known to exist, could indicate whether these faults are generating microearthquakes. The survey may find microearthquakes to be aligned in space, but not matching with the known faults, which may indicate the presence of a new seismotectonic structure. In other cases, microearthquakes may be found scattered in space and no seismic zone or lineament can readily be identified. In such a case it may be necessary to extend the coverage of the microearthquake network in order to cover extension of the faults present in the area to assess their degree of seismicity. It should be noted that observing no microearthquakes during a period of operation of, e.g. a few years does not guarantee that the region is aseismic.

3.1.6 Spatial and temporal changes in microearthquake activity

Three years of operation of a microearthquake network may reveal lateral and/or vertical migration of microearthquake foci and variations of microearthquake activity in time. The pattern of migration may have a recurrent characteristic and may be associated with some known geological faults [3].

A swarm of earthquakes may be recorded during the survey. If an earthquake of moderate size has earlier occurred in the region, the network would record its aftershocks, the number and magnitude of which would decrease with time. In such a case, if the return period has been established on the basis of instrumental and historical data, there would be reasonable confidence that the site is still in the aftershock decay sequence.

3.1.7 Evaluation of attenuation of ground motion with distance

The amplitude of ground motion can be inferred from the motion recorded on the seismogram. When the same microearthquake is recorded at several stations at different distances, some additional information regarding the attenuation characteristics for seismic motions in the region can be obtained.

3.1.8 Intensity-magnitude relationship

If several earthquakes, severe enough to be felt by man, occur during the operation of microearthquake network; their magnitude and felt area could be estimated and on the basis of these data, a relationship between the felt area and magnitude could be established. This relationship, then can be used for determination of the magnitude of some historical earthquakes for which only the felt areas are available.

3.1.9 Evaluation of the frequency-magnitude relation

The frequency of occurrence and the corresponding magnitudes of earthquakes in a region can be related by Gutenberg-Richter magnitude - frequency relation [4].

$$\log N = a - bM$$

where: N is the number of earthquakes with magnitude equal to or greater than M

a,b are regression constants

Depending upon the stationarity of the rate of seismicity in the region, the regression constants can be estimated after the network has operated for some time.

3.1.10 Integration of microearthquake results with available geological and geophysical data

After the network of microearthquake recording stations has been operated in a region for about a year and some useful information regarding the microearthquake occurrence has been obtained, it is necessary to integrate this information with other available geological data for better interpretation of the results.

It is important to combine the information obtained during the microearthquake survey with available data on both instrumentally-recorded and historical earthquakes that may have occurred in the vicinity of the region under investigation. Frequently, as a result of the microearthquake survey, a seismic zone or lineament (or its extension) can be associated with a historical earthquake which previously may have had some uncertainty in its location. Such information is extremely helpful for estimating the potential of the seismic zone lineament to generate a future moderate - to large size earthquake.

Detailed geological information, particularly that corresponding to the neotectonic movements, should normally be available for the region at the start of the microeathquake survey. Additionally, major lineaments should be picked up from satellite imagery and the result of the survey should establish whether any of these lineaments or their extension show microearthquake activity. Other available geological and geophysical data, such as gravity anomaly, magnetic anomaly, basement topography should also be investigated to examine their relationship, if any, with the microearthquake activity.

For most regions of the world, information on instrumentally recorded earthquakes is limited to the past 100 years or so, and that on the historical earthquakes to the past 300 to 400 years. However, in recent years, it has become possible to investigate prehistoric earthquakes through radiometric dating and archaeological studies of earthquake induced sedimentary structures preserved under favourable geological environment [5]. When possible such information, obtained by trenching earthquake faults, should also be integrated with the results of the microearthquake survey, particularly in cases where instrumental and historical seismicity data are scarce.

3.1.11 Examples of results obtained from microearthquake surveys

The usefulness of conducting microearthquake surveys has been amply demonstrated in the literature. Through a microearthquake survey a major tectonic feature near the Manila Bay, otherwise not known was identified [6]. A definite correlation between the known structure and distribution of microearthquake foci was obtained [7] by conducting a microearthquake survey in the Mid-St. Lawrence Valley Charlevoix Zone, Quebec. Locations and focal mechanisms of microearthquakes in the Livermore Valley, California contributed to the comprehension of the regional tectonics [8]. Poisson's ratio at different locations and inferred tectonic implications in the vicinity of the Geysers in California was obtained from a study of microearthquakes [9]. A technique to use S-to-P wave amplitude ratios of microearthquakes to investigate focal mechanism was developed [10]. The effects of attenuation and site response on the spectra of microearthquakes in the northeastern Caribbean was found [11]. Microearthquake survey is useful in investigating reservoir-induced seismicity [12]. It should be noted that in investigating the seismicity induced by reservoirs it is important to collect data before and after filling the reservoir.

Specific use of a microearthquake survey in nuclear power plant decisions has been made in a number of countries. Few examples of such a use in member states is given in Appendix A.

3.2 Limitations

When carrying out a microearthquake survey any of the following factors may limit the possibility of obtaining reliable results:

- complicated local characteristics;
- possibility of various interpretation of the results;
- the need for large extrapolations.

3.2.1 Complicated local characteristics

Where background seismic noise is very high, instruments cannot be operated at the magnification level appropriate for recording smaller microearthquakes. Often, difficult logistic conditions may not allow location of seismic stations at the most appropriate place. This results in loss of useful data and lowers the quality of the focal parameters to be determined.

In certain cases of complex geology, particularly when severe lateral heterogeneity exists in the region, it is more difficult to locate the microearthquakes accurately.

In cases where the region under consideration is bounded by coastline, two particular problems arise. Firstly, the ocean generated microeseismic noise may not permit operation of seismic stations at a desirable magnification. Secondly, since routine operation of ocean-bottom seismographs is difficult, the regional coverage by seismic stations may not be adequate for locating microearthquakes with desirable accuracy.

There may be other site-related logistic problems limiting the use of microearthquake surveys, such as non-availability of reliable commercial power supply, rough terrain and difficult access.

3.2.2 Possibility of various interpretation of the results

The interpretation of the data obtained from a microearthquake survey may require a great deal of judgment. For instance, for several reasons epicentral locations may not always align with the surface expressions of a fault/lineament, e.g. due to location uncertainties, dipping of the fault or a comparatively wide fault zone. Identification of the discrepancies in such cases has to be made with judgment. Particular care and experience is also needed in evaluating composite fault plane solutions, where it is assumed that the microearthquakes included in a particular set belong to the same population.

3.2.3 Extrapolation of the results

Particular care is needed when extrapolating the results obtained from microearthquake surveys. Extrapolation of microearthquake data, for example to estimate return periods or regional attentuation and magnitude-intensity relationships for moderate or large magnitude earthquakes should be done with great caution.

4. PLANNING A MICROEARTHQUAKE SURVEY

The planning for a microearthquake survey could be divided as follows:

- Preliminary investigations;
- Study of environmental conditions;
- Planning of the observation.

4.1 Preliminary Investigations

4.1.1 Collection of Available Information

Available information on seismicity and geology of the region should be collected and studied before conducting a microearthquake survey.

4.1.2 Reconnaissance Microearthquake Survey

Reconnaissance microearthquake surveys are performed using three or more mobile seismometers [13] to obtain an approximate seismicity pattern of the region. This survey, combined with the data on seismicity and geology of the region allows development of a preliminary plan for the microearthquake network. This survey is particularly useful where there is no background seismicity information.

4.1.3 Ground-Noise Level Survey

Ground-noise level surveys may be performed with two mobile stations to obtain relative ground noise level between two locations. This survey is useful in deciding the station locations taking into account the logistic conditions.

4.1.4 Telemetry Tests

Radio transmission tests are performed to check the radio connections between the stations and the central recording laboratory. It should be noted that checking topographical maps alone, in order to ascertain the line of sight, is not sufficient.

In cases where the use of telephone line connections are considered, detailed tests of the transmission quality should be done before deciding on the instrumentation.

Radio time-signal reception conditions should be tested on a 24-hour basis at each proposed station location.

4.1.5 Power Supply Availability

Conditions of commercial power supply should be investigated at each proposed station, preferably on a 24-hour and 365-day basis. Voltage and cycle variation ranges should be assessed together with frequency and duration of power supply failure in order to decide on the size of the back-up power supply to be provided. If the voltage fluctuation is due to a particular power consumer in the general area, it may be useful to arrange for an independent power supply connection, if necessary, with a dedicated transformer. Use of solar power supply should be considered whenever possible.

4.2 Influence of the Environmental Conditions

The study of the environmental conditions is of great value for planning a microearthquake network. The type of recorders to be used, the design of the seismometer vault and recording house, anti-lightning measures and grounding for the electric apparatus are all sensitive to the environmental or climatic conditions of which prior detailed studies are therefore required. Extreme humidity prohibits certain recording methods and; extreme temperatures restrict certain electronic devices.

Unpacking of the transported equipment should be carefully planned, in order to avoid damage from rain, snow etc.

4.3 System Design

Based on the above investigations it is possible to evaluate the network system design. This will include the network configuration, sensitivity of the instruments, the type of recorders, the recording speed, the time marks and coding for the records, the trigger level and delay time for the event recorder.

The network should appropriately cover the area to be studied. The accurate determination of horizontal location requires stations surrounding the epicentre area in different azimuth and the accurate determination of the depth requires a station in the centre of epicentral area.

The characteristics and location of the microearthquake network depends on the nature of the earthquakes to be studied, particularly on their focal depths. For investigating shallow microearthquakes, (focal depth less than 20 km) over an area of 30 km x 30 km, a network with eight stations may be adequate. This should include several 3-component stations (usually three) and at least five vertical-component stations. The stations should either run independently or be telemetered to the central base station by radio or telephone line.

4.4 Planning of Observations

The noise level survey can be completed within one month. Reconnaissance observations with three stations may be continued for several months, depending on the level of the seismicity in the region. These data are also useful in deciding the numerical parameters to be used as a first approximation for processing of the data and interpreting the results, e.g. Vp/Vs used for Wadati-diagram (P versus S-P diagram to obtain origin time), P-wave velocity used for the location etc. The network routine observations could then start and should be continued for at least three years (for the initial period temporary stations may be added to obtain useful information on crustal velocity structure, discrimination of explosions and microearthquakes, V_p/V_s ratio etc.).

5. INSTRUMENTATION

5.1 General Considerations

The two basic components of the instrumentation are the sensors and the recorders. The recording could be performed locally and independently at each station or the signal from each sensor could be transmitted to a central recording facility through telephone line or radio link. In either case, the sensors are identical; however the procedure of recording can be different.

Because the instrumentation for the networks have been developed by many independent groups in several countries, it is difficult to present a comprehensive review of equipment and their calibration methods. In general, however, a network includes seismometers, signal conditioning devices (Frequency Modulation, or Pulse Code Modulation Amplifier, Automatic Gain Control, Galvanometer etc.), signal transmission circuitry (if telemetering system is used), recording, timing and coding equipment, and power supplies.

The seismometer should be placed several hundred meters away from roads with heavy traffic. It should also be sited away from all possible sources of cultural noise.

5.2 Characteristics of the Network

5.2.1 Sensors

The frequency range to be observed is from 1 to 30 Hz. The dynamic range of recording should be as wide as possible in order to allow recording of microearthquakes in a range extending from a magnitude as low as possible up to magnitude 4. The actual range of magnitude should be determined based on the preliminary survey. The density and number of instruments may need to be increased depending upon the level and number of earthquakes recorded. It may be useful to have one instrument set to the high range in order to capture earthquake records for the larger earthquakes.

Flexibility in establishing and operating the network is, by nature, necessary in order to affect the acquisition of the most useful data from the network. For example, if magnitudes less than one are more common, then a denser network may be needed, if most of the earthquakes are greater than magnitude 2 then fewer and more dispersed stations would provide better data.

It should also be noted that the major cost is in establishing the basic network operation and administrative procedures, so the addition of more seismographs would be a small percentage of the total cost. The network should be supplemented with one or more strong motion accelerographs if the activity remains at a high level in order to acquire ground motion data. It is desirable to have the upper range of recorded magnitudes overlapping with those that can be recorded by other networks. The highest possible sensitivity should be used for the vertical component, in order to enable the sensors to pick up sharp "P" phases. The horizontal component could be operated at lower magnification, sufficient to pick up "S" phases and to record maximum amplitude.

Relatively low natural frequency (1 Hz) seismometers with test coils should be used. The instruments must be damped with a damping coefficient between 0.7 and 1: with damping coefficients less than 0.7, the response of the sensor biases the recording and tends to invalidate the spectrum.

5.2.2 Timing

Time marks generated by master clocks are required even if radio signals are available; the Universal Time from radio signals should be recorded on paper several times (at least twice) a day. A time code identifying minutes, hours (and possibly every sixth hour) and date is essential, whereas for telemetry transmission, code marks for every second are also required. The master clocks can be piloted either directly by radio signal or can be checked at the beginning and end of each sheet by the same means. In the case of a centralized system (telemetry transmission) a common time base can be used for the entire network. This would eliminate the need for separate clock correction for each station. It is important that extensive attention be paid to timing considerations because if accurate timing is not provided then the locations of events will be systematically in error.

5.2.3 Recording

Recording is arranged either independently at each station, or recorded data are transmitted from each station through telephone line or radio link to a central recording facility.

From the seismological viewpoint central recording with telemetering is preferable to separate recordings of independent stations. However, in some cases practical and logistical considerations may suggest adoption of a network of independent recording stations.

Continuous recording is generally accomplished using helical drum recorder. This is necessary for:

- monitoring regular operation of the instrument, and
- recording events small enough to be recorded only at one or two stations.

If telemetery is not used, continuous recording is vital because triggering at each independent station is not necessarily very reliable. If, for some logistical reason, daily inspection is not possible, then use of long-term recording with suitable higher speed recorders that do not require the change of paper everyday is essential [14, 15]. In any case paper speed of at least 4 mm/s is necessary to assure proper time accuracy for microearthquake observations by analog recording.

In telemetering systems, continuous recording with chart recorders may also be suitable. This permits interpretration of the seismograms by comparing simultaneous signals on different channels. It is not however practical for assessing the events of a day at a glance for which, even in the telemeter recording centre at least a few visible drum recorders are necessary.

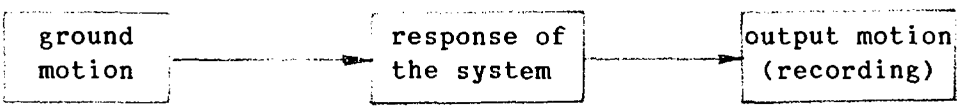
Event recording using delay-trigger devices is useful especially for telemetered central recording [16]. Either magnetic tape recorders or visible chart recorders can be used. For magnetic tape recording, digital recording may be useful for further data processing with better N/S ratio. The recording can be triggered with different methods, but in any case it is convenient to combine signal levels from a number of stations.

If delay-triggered recording is adopted for a telemetered microearthquake network and signals from several stations are used for triggering, the operator may change the trigger levels at certain stations, exclude some of the stations and include others, depending on the ground noise levels or electric noise due to telephone line engineering works or radio transmission disturbances. Delay time may also be changed, if necessary.

For selection of a telemeter system, the results of the preliminary investigations (see sub-section 4.1) should be taken into account. Radiotelemetery may be used when the substations can be seen directly from the main stations, power supply is available at all stations and radio-electronic expertise is available. Telephone line telemetering can be used when good quality telephone lines connection are available. Advantages and disadvantages of analogue and digital transmission depend on different seismological and practical viewpoints and therefore, no straightforward conclusion can be given.

5.2.4 Instrumental response of the system

The frequency response of a seismic system describes the relative amplitude and phase with which the system responds to ground motion.



The response of the system can be obtained in the time domain and in this case the input signal could be generated by the seismometer mass release test. This corresponds to applying a step function in ground acceleration. If the system has a time invariant linear behaviour, the frequency response (complex function) is the Fourier transform of the response in the time domain.

The automatic calibration unit in the field package can generate a daily sequence of transient calibration signals. Several theoretical approaches for calculating system response from these signals have been developed: Fourier transform technique, which determines the response of the complete system through the observed input and output signals [1, 17] and least square techniques which largely involve analytical methods to compute the system response [18].

5.3 Installation and Initial Calibration

5.3.1 Construction of stations

After station locations are determined on the basis of seismic noise level survey and logistics needs, the seismometer should be placed, whenever possible on hard bed-rock. Where geophone type sensors are used, these need to be properly buried to ensure good ground contact. With larger seismometers a base or vault is constructed and seismometers are levelled. A drainage system and possible protection measures against human and animal intrusion into the seismometer surroundings have to be provided. Care should be taken to avoid locating seismometer near large trees in order to avoid ground noise generated by wind. Where a vault is constructed, it should have an adequate surface area (about 1 m x 1 m) for accommodating possible future additional sensors. The base should have convenient height (about 1 m) for the manipulation of the seismometer but not so high that unstable self-oscillation is generated, this consideration is especially important when recording the high frequency motion.

The vault can be separated by several hundred meters from the instrument house where recorders or telemeter equipment are installed. However the seismometer cable should not be laid near AC power lines.

The instrument house should have convenient access for installation work and the daily visit of the station keeper.

The use of bore-hole seismometers is recommended when no quiet foundation is available near the proposed station site. It should be noted that only high frequency noise including acoustic disturbances (higher than several Hz) can be reduced by using bore-hole of shallower than 100 meters or so. To eliminate the microeseismic noise of frequency less than 1 Hz, it is necessary to use bore-holes deeper than several hundred meters. Shallow pits or tunnels may help ground-noise reduction and making use of natural or existing ones is therefore advantages.

All construction related with the station should be completed at least several weeks before the installation of the equipment in order to have the vault and instrument room in a sufficiently dry and stable condition.

Cables for power supply, transformer, earth conduction for the electronic equipment and the lightning arrestor should be installed before setting the seismometers.

True north direction (magnetic north plus geomagnetic declination) should be marked in the vault for the easy setting of N-S and E-W component seismometers. In using the magnetic compass, attention should be paid to environmental conditions which may result in magnetic anomalies. Convenient portable equipment to obtain the true north, based on sun dial principle, are commercially available [19, 20].

5.3.2 Calibration of instruments

The overall characteristics of the system have to be calibrated carefully using electric signal generators and if possible by mechanical vibration (shaking tables).

Beside the electrical and mechanical adjustments and calibration of seismometers with recorders, it is necessary to perform test observations in the central institute before the seismometers are distributed to separate field stations. To perform this test all seismometers should be placed together in the same room with horizontal component seismometers all in the same direction (e.g. NS). Simultaneous high speed records of microtremors with sufficiently high sensitivity should be taken for all seismometers with their electronic dials set at the same position.

The above procedure is indispensable for knowing the degree of similarity of records among seismograph which are going to be distributed to different locations. Individual electrical and mechanical adjustments do not necessarily assure exact similar record of earthquake motions. Therefore, this parallel test recording should also be performed for the actual earthquakes, continuing the observation until a few seismic records are obtained. The records thus obtained will be strong support, when quite dissimilar seismograms are obtined at different stations.

This test of horizontal seismometers is essential for selecting a pair of NS and EW seismometers with as similar characteristics as possible to be placed at one 3-component station.

Before the installation team leaves the field station, records of ground noise with elevated sensitivity and of at least a few records of actual microearthquakes in routine condition should be obtained to confirm proper operation, and brought back to the centre for analysis by seismologists.

The natural frequency, open circuit damping and sensitivity of the seismometer (and Galvanometer, if any) must be evaluated.

5.3.3 Calibration of the network

The microearthquake network can be calibrated by explosions as well as by actual earthquakes. The records of the events at each station can then be compared and any exceptional or strange recordings, at a particular station, is taken to suggest the improper operational state of that station.

Larger events outside the network should be recorded almost equally at all stations. The apparent arrival of P-phase from such events can then provide information on the velocity structure.

6. OPERATION, MAINTENANCE AND DATA STORAGE

In general, operation of an independent station with drum recorders, needs a daily visit by the station keeper to change recording papers and to check the clock to the radio time-signal. This daily visit also enables the station keeper to monitor the proper operation of the instruments. Possible changes in the instrument and environmental conditions can also be observed and reported to the central station by the station keeper. If long-term recorders such as those used in Japan are adopted, the visit may need to be weekly or monthly. At the central station seismograms should be collected for interpretation as often as possible, at least once a week.

It is essential to write or stamp the station name (or code), date and time (in Universal Time) of the first and last minute marks*, instrument name, component and direction of earth's displacement** on every sheet. Although it may seem superfluous for the station keeper to repeat the name of the station, instrument etc. on every daily record, the procedure is,

---

* The given time should be from the clock, adjusted within 0.01 s of Universal Time. The time correction, should be noted explicity on the sheet. Universal Time, year, month and day should be written numerically.

** Recorders should be designed as to give seismograms with increasing time from left to right and from top to bottom on the sheet and ground displacements upward, northward and eastward from bottom to top respectively. Care should be taken to assure appropriate calibration of instruments to acquire the information in the form discussed above.

however, indispensable because the sheets or their copies may be separated from each other and mixed with other station seismogram sheets which would make the identification of the station and instrument difficult.

Records of environmental disturbances such as lightning, artificial explosions, nearby construction works etc. that have been recorded on the seismograms, should be noted on the record sheet. This information will be very useful during interpretation of seismograms. Electric noise due to power line disturbance, telephone line engineering works and radio transmission disturbance should be noted, if they are recognized as such.

If a blackout, due to a main power supply failure, continues for a longer period than that allowed for by the backup battery capacity, the station keeper should adjust the clock with the radio time signal and note the period of power failure (from the start of the blackout to the resumption of operation). To avoid such difficulty it is necessary to provide instruments that could be fully operated by automatic systems which could resume their normal operation after the recovery of power supply. It is recommended, however, that, at least, the clock and the radio for receiving the time signals be operated by a DC source, in order to ensure complete continuity.

Records of calibration signal given to the seismometer test-coil (about once a day or so) can confirm the normal operation of the instrument. Regular inspection of seismograms is indispensable for keeping the instrument in order and it should never be neglected, even when no seismic events are actually recorded.

Any unusual form of recording on each seismogram should be compared with records at other stations to ensure proper functioning of instrument.

All seismograms should be sorted in chronological order, classified by station, instrument and component, and stored in a suitable environment. They should also be easily retrievable.

7. DATA PROCESSING

7.1 General

Microearthquake surveys will provide one or more of the following:

- Arrival times of P, S and other phases, including maximum values
- Their amplitudes and periods
- Signal duration
- Direction of first motion.

Depending on the extent of the information retrieved from the records, it would be possible to determine for each microearthquake:

- Origin time
- Epicentre (latitude, longitude)
- Focal depth
- Magnitude.

For accurate source locations it is necessary that the latitudes, longitudes and elevations of the stations be known within 25 meters. It will be useful to mark the station locations on a 1:25,000 map or a more detailed map, if available. Simple traverse survey from a nearby monument (triangulation point or leveling bench mark) or from an identifiable object shown in the detailed map is recommended for obtaining a more reliable position. Recent increase of accuracy of satellite based navigation positioning should be introduced if possible.

7.2 Reading Records

Accuracy in onset times is an important factor in locating the events. The desired accuracies in source location require that individual onset times are estimated, at least, within 0.05 seconds. It is therefore necessary that time corrections if any (see sub-section. 5.2.2) be taken into account while estimating the arrival times of the seismic phases. Accuracies in onset times of this order are achieved easily for P-waves because of their sharp onsets (provided the paper speed is not less than 4 mm/s). The use of an x - y digitizer is helpful in reading the onset time, period and amplitude of seismic phases. P times should be read on vertical component records and S times should be read on two horizontal records. The vector sum record of the two horizontal components will also be helpful. All distinct phases near P and S should be read. Processing might reveal the nature of these phases. For an impetus onset, the direction of motion should also be noted.

The precision depends upon the quality of the recording (thickness of line) noise level and the nature of the first motion (impetus or emergent). For impetus and emergent phases, the onset time can be read with an accuracy of 0.02 s. and 0.2 s., respectively, when magnetic recordings are played back at high speed.

When the epicenter lies well within the recording network, an error of 0.1 s, may displace the epicentre by several hundred meters. When the epicenter lies beyond the network's periphery, this time error may result in error of up to several kilometers. It may also be possible to achieve better accuracies in onset times amplitudes and duration of the signals in a central recording system by replaying the signals using higher sensitivity and higher paper speeds to produce a multichannel record.

7.3 Filing Records

The number of records from the microearthquake survey tends to increase very rapidly. It is therefore necessary to keep each record marked with easy and clear identification signs (see section 6.).

The records may be filed in some predeterminded order, and care should be exercised to ensure that the adopted storage order is maintained throughout the survey. It is also desirable to provide adequate space for storing seismograms and to maintain an up-to-date inventory. Station codes should be changed, when location is shifted by more than 25 meters.

7.4 Bulletins

To use the data efficiently, station bulletins issued at regular intervals are recommended. Preparing the bulletins also helps to keep a check on the proper functioning of the network. The bulletins may contain information on as many observations as possible and on the judgements of the seismologist in classifying a shock as local, near or teleseismic. Phase names may be followed by component such as PZ, SN etc. In exceptional cases, where different instruments are used at different stations, instruments should be identified by name, e.g. PZ/S-13 (P wave read on vertical component recorded by S-13 seismometer). If there has been excessively high background noise, sufficent to deteriorate the detection capability significantly during the period of the bulletin, the period should be mentioned.

7.5 Selection and Editing of Events

Event detection requires picking up the time of the first arrival. In case of a drum or chart recording, onset times may be read by scanning the records deploying a scale and a magnifying glass in visual check of the signals of microearthquakes. If the data is recorded on analog magnetic tapes, a semi-automatic or automatic procedure may be used for finding the approximate positions of the events on the tape. For instance, by playing the tape back at higher speeds, the earthquakes can be made audible. Alternatively, a triggering unit based on sensing proper built up signal (or coincidence detectors in case of multichannel data) may be applied. A procedure for picking the first arrival automatically with a computer may also be adopted [21, 22]. Selected portions of the data can be digitized. One hundred samples per second per channel would be adequate, provided the analogue signals are suitably filtered to cut out high frequency noise [23]. It is necessary that about 10 seconds of data before the P-onset be included in the data stored on to library tape. The library tape may contain about two minutes of data per event, the actual duration of storage being determined for the region to be monitored. It is also necessary to include the full time-code (in case of continuous time signals). With digital storage it is possible to record the complete time information i.e. the absolute time at the beginning of each record and the sampling interval; this enables the absolute time at any instant to be reconstructed during processing. The coded time signals can also be stored along with the main data signals. The wave forms of the edited events can then be stored on the digital magnetic tapes along with the time information. Where digital recorders have been deployed in primary recording, a computer may be used to scan and edit the digital tapes on to library tapes.

7.6 Data Analysis

7.6.1 Identification of events

Generally earthquakes may be identified on the basis of their abrupt beginnings, distinct P and S arrivals and their slowly decaying coda. Smaller shocks, for which these details are not so clear, may be compared with larger shocks from the same area on the basis of their frequency content, signal decay patterns etc. It may be useful to note here that the frequency of the recorded maximum amplitude of earthquakes with magnitudes between 1 and 4 varies considerably.

One of the most troublesome tasks in identifying microearthquakes is discriminating between microearthquakes, artificial explosions and rockbursts. Contact should be maintained with agencies or companies carrying out explosions in the region. Detailed information on their explosions can be correlated with the characteristic seismic features observed on the microearthquake records.

7.6.2 Location of events

Origin time of an event may be first determined by Wadati-diagram using S-P intervals and P arrival times. To obtain hypocentre co-ordinates and origin time simultaneously by P arrival times alone may sometimes lead to bad convergence and inadequate location. It should be noted that S arrival times read from the vertical component record can also lead to erroneous determination of location, because of false S phases such as converted P at crustal discontinuity. Vp/Vs from the Wadati-diagram gradient may be obtained by the least square methods as the events are accumulated. Initially, Vp/Vs given by previous observations (or a theoretical value) may be taken. Events may be located using a hypocentral location programme such as the HYPO71 [24]. The P as well as the S times should be utilized, as much as possible in locating the hypocentre. The accuracy of source location depends on knowledge of the travel time curve (which in turn depends on knowledge of the crustal velocity structure), the distribution of seismic stations and the accuracy of arrival times. The likely errors and their distribution for the chosen network may be determined through simulation studies based on the structure and location techniques [25] or through Monte-Carlo methods [26, 27].

7.6.3 Determination of velocity structure

The arrival times of the seismic phases provide information on the seismic velocity structure for the paths travelled. Using these observations (provided that the total number of observations exceed four per earthquake) the crustal velocity structure can be determined using a least square modelling procedure to obtain simultaneous estimates of the hypocentre parameters and the velocity structure [28, 29]. If there are indications of significant lateral variations in the velocity structure (as when the area under investigation includes regions from different tectonic provinces) a three-dimensional approach may be adopted for determining the velocity structure [30].

It is advisable to use calibration blasts at suitable locations in the vicinity of the area of the microearthquake network to construct regional travel time and thickness and depths of various layers [31]. Wherever possible, quarry blasts or construction related detonation can be utilized for this purpose. In absence of such blasts in the area six to twelve calibration blasts (about 50 kg TNT) would be adequate, depending upon the efficiency of seismic wave transmission. Smaller charges at shorter distances may also be necessary if severe lateral heterogeneities are encountered. This gives information that is useful in improving the precision of locating the microearthquakes. Where a region is characterised by dipping layers and/or severe lateral heterogeneities, necessary care needs to be exercised in computing the hypocentral parameters and using ray tracing techniques for non-homogeneous media [32].

7.6.4 Magnitude determination

Determination of magnitudes of the microearthquakes may be based on the recorded signal amplitudes or signal duration. Until such times when a suitable magnitude duration relationship is determined for the region, the response of the Wood-Anderson seismograph (on which the definition of M_L is based) corresponding to the recorded amplitude may be computed [33]. A relationship between earthquake magnitude, signal duration and hypocentral distance in the following form may be established:

$$M_D = a_1 + a_2 \log\tau + a_3\Delta + a_4 h$$

where:

M_D is duration magnitude
τ is signal duration (s)
Δ is epicentral distance (km)
h is focal depth (km)
and a_1, a_2, a_3 and a_4 are regression constants

A selected set of well-recorded earthquakes should be used to establish the duration magnitude scale (see Appendix B). The duration of the signal may be defined as the time interval between the signal onset time and the time when the signal has declined to twice the background noise.

7.6.5 Statistical analysis of data

Statistical analysis of the data can potentially reveal several aspects of the seismicity in the site area. For example, microearthquake activity may be studied for each recording location separately. Recording should be carried out for a period long enough to allow representative conclusions regarding the variation of seismic activity in space and time. Histograms indicating the number of earthquakes per unit time may be drawn for each site. The S-P travel time information may be incorporated in the histograms [34]. A plot of hours versus number of earthquakes may be made and the data may be tested for randomness [35]. This is beneficial, because if it can be demonstrated that the departures from randomness are small, statistical procedures can be applied to the data [36]. The entire data set within a specified hypocentral distance (say S-P interval less than 5 s.) may be investigated for estimating the mean activity in the site area. The data should be tested to examine whether a relation of the type

$$\log N = a - bM$$

can be fitted to the observed data, and a, b-values can be determined for the data set. Also the errors in these estimates should be evaluated. If b-value estimates for the region based on large magnitude earthquakes are available, the two estimates should be compared to see if the microearthquake can be utilized to check the maximum earthquake potential for the region under investigation.

7.6.6 Waveform analysis

Spectral analysis of a selected set of well recorded seismogram waveforms enables determination of the corner frequency and the Q-values and estimates of some source parameters for the seismic region [11, 37]. Records obtained on bedrock (if available) may be utilized to infer transfer functions (which influence various parts of the spectrum) of the site region and compared with those based on theoretical models. For computing spectral amplitudes, the earthquake signals should be digitized as sampling rates which are sufficiently large to overcome frequency aliasing. Determination of spectral parameters is generally dependent on the signal length, for Fourier analysis. The actual length of the signal for Fourier analysis may be chosen through a trial and error process by carrying out the analysis for several signal lengths [38]. When possible, spectral analysis should be carried out to both the P and S components [39].

8. PREPARATION REPORTS AND INTERPRETATION OF RESULTS

An important consideration in the proper operation of a network is the careful reporting of the data acquired and interpretations that have been made based on those data. These reports are to be prepared and issued at regular intervals which can be selected based on administrative requirements. In most cases the reports are issued quarterly and contain, at least, the following information:

- Total duration of the microearthquake survey (when it was started and when it finished)

- Duration for which a major part of the network was operational (i.e. the period for which the data have been used in interpreting the results)

- A table of recorded earthquakes, including epicentral/hypocentral locations and providing magnitudes and associated errors. The located and identified events should be separately described at each station (classified by S-P intervals)

- The data should be displayed on maps and include an accumulation of earthquakes as well as a listing and plots of events in different time intervals

- Number of events identified as blasts, rockbursts etc.

More substantial reports would usually be issued on a yearly basis and a complete final report is prepared at the termination of the microearthquake survey. These reports may include all the data reported in the shorter term reports as well as the following:

(1) The scope of the survey determined from available information on instrumental and historical earthquakes and other geological and geophysical data

(2) The configuration of the chosen network displayed on maps, the characteristics of the seismograph and the data processing equipment

(3) The known geological structure whose seismic activity might be inferred (if possible with some classification e.g. potentially active, moderately active, inactive or uncertain)

(4) The seismic wave velocity structure adopted for locating sources of microearthquakes

(5) Characteristics of the site and region under investigation that have been inferred on the basis of the microearthquake survey data (e.g. P- and S-wave attenuation constants)

(6) Traces of characteristic seismograms from specific regions (preferably, multichannel records)

(7) Comparisons of microearthquake activity of the area obtained by the survey with longer period seismicity of a broader region that includes the investigated area. General conclusion for the seismicity of the area

(8) The extent of the information that the microearthquake survey data have been able to provide in relation to the stipulated object of the report. Recommendations for extension of the microearthquake survey along with explanations of their rationale

(9) Limitations of the survey (if any, see sub-section 3.3), the noise conditions at the site, the period of satisfactory

operation and the quality of data (excellent, good, satisfactory, below average) and the factors responsible for this quality

(10) Special features and interpretations of the observed microearthquake activity, if any e.g. microearthquake swarms in space or time, variation of microearthquake activity etc.

To make a tectonic map, the location of the microearthquake network and the well-located microearthquake marked on one map can be attached. Magnitude information (preferably in half-magnitude steps, e.g. 1.0, 1.5, 2.0, etc.) may also be given for each microearthquake identified.

APPENDIX A

Examples of Microearthquake Surveys for Nuclear Power Plant Siting

The following is a few examples of specific use of microearthquake survey in nuclear power plant siting in Member States.

- The San Onofre nuclear generating station used a microearthquake network installed along the christianitos fault to show that there is no seismicity associated with that fault.

- In 1981, the Southern California Edison Co. used data from the existing Cal.Tech-USGS network to investigate an earthquake swarm which occurred off the coast of California near the site. From the locations of the events it was demonstrated that they occurred on a specific fault offshore.

- The Tennessee Valley Authority and the Tennessee Earthquake Information Center are actively studying the microearthqukes in the eastern Tennessee area with an extensive microearthquake network. This information is to be used to determine the size and orientation of seismogenic structures in that region.

- Examples of a microearthquake survey and some typical results

  Fig. A-1 is a schematic diagram of the observation system (section 5)
  Fig. A-2 is obtained seismograms in three components (section 5).
  Fig. A-3 indicates the possible correlation of seismically active fault with epicenters of microearthquakes (sub-section 7.6.2)
  Fig. A-4 is one of the examples of the relation between durations and magnitudes of earthqaukes (sub-section 7.6.4).
  Fig. A-5 is results of statistical analysis incorporated with macro- and historical earthquakes (sub-section 7.6.5).

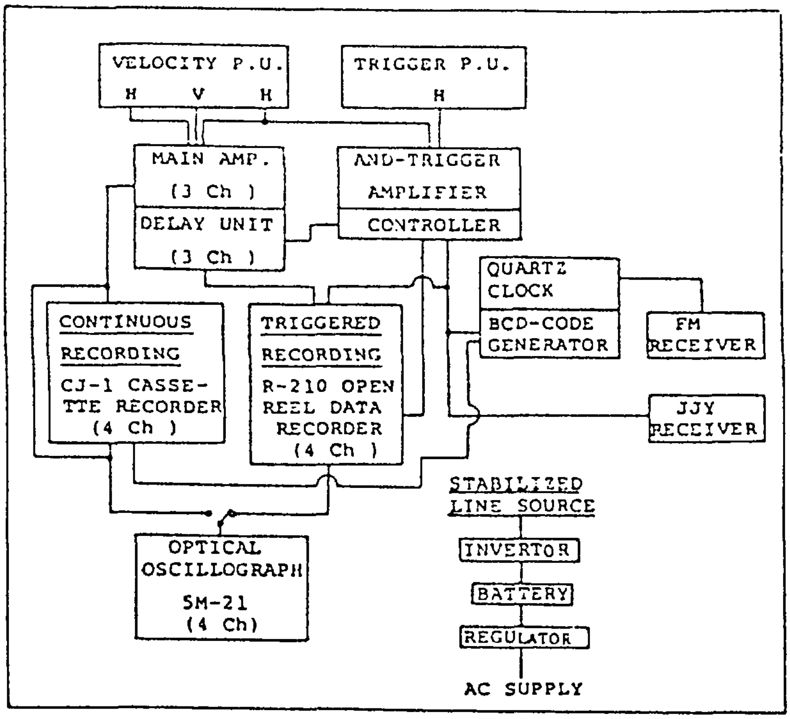


Fig. A-1 Schematic Diagram of the observation system at individual stations

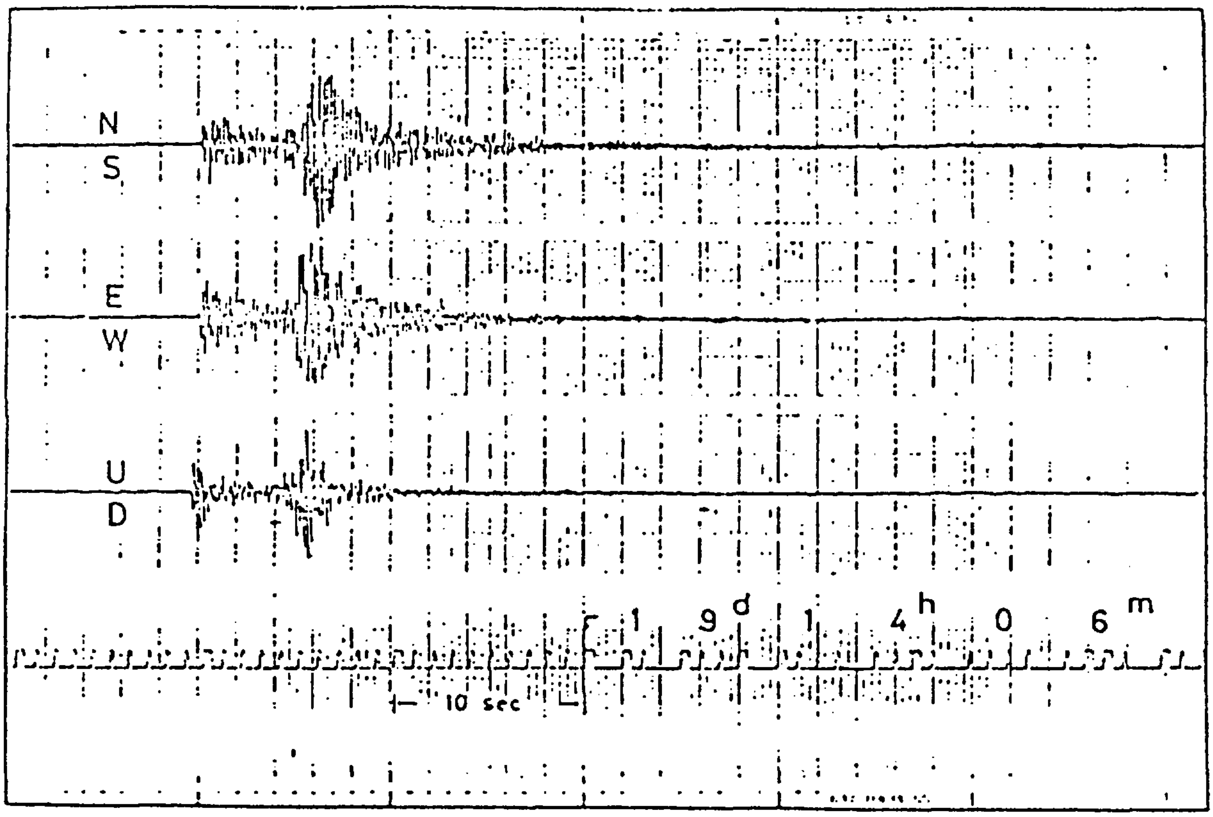


Fig. A-2 A representative record form of a Micro-Earthquake detected on Continuous Casset Recorder and displayed on a chart of Pen Oscillograph and used as supplemental data for evaluating statistically the seismicity of the region

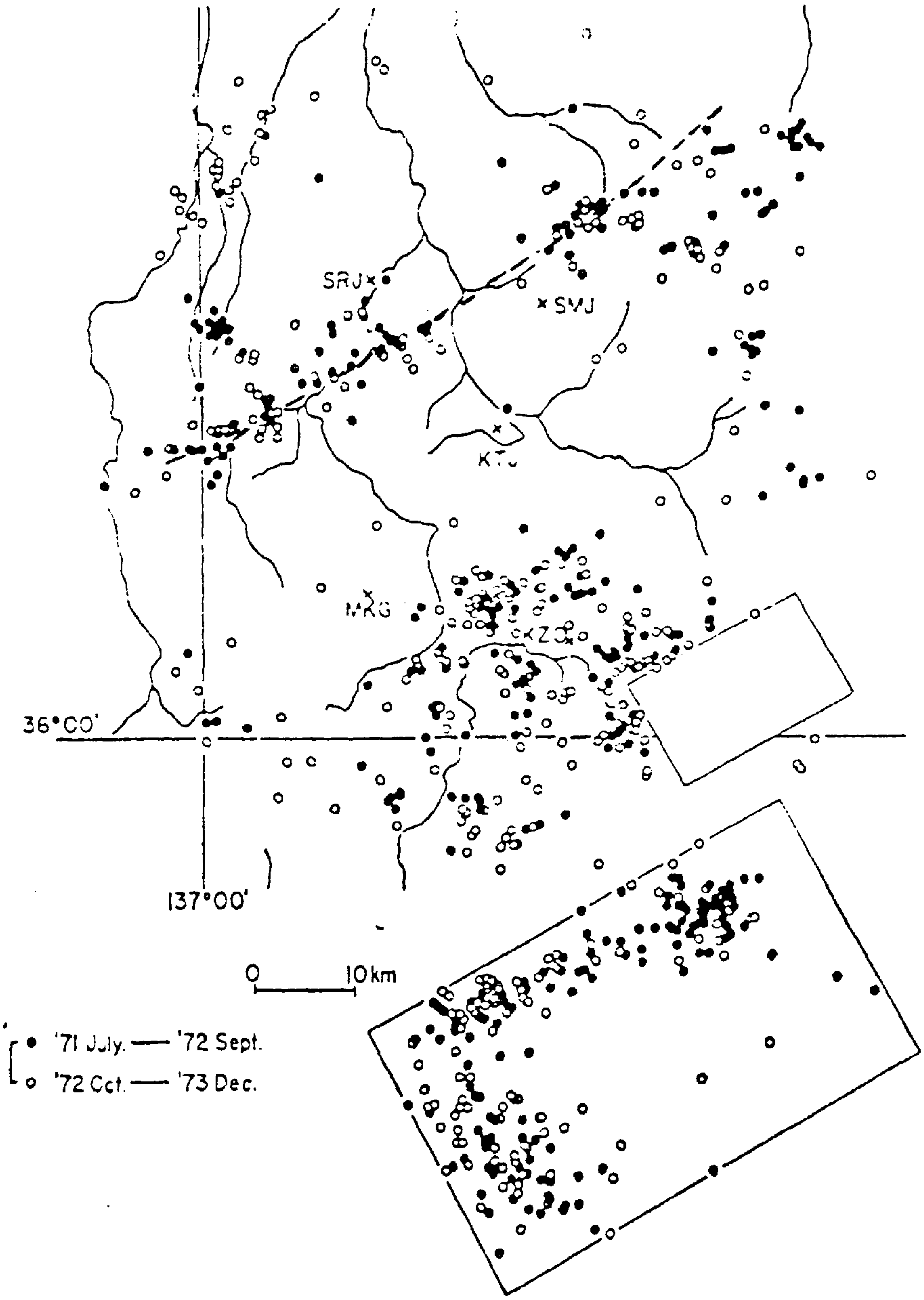


Fig. A-3 Composite epicentral distribution in the periods July, 1971-September, 1972 and October, 1972-December, 1973.

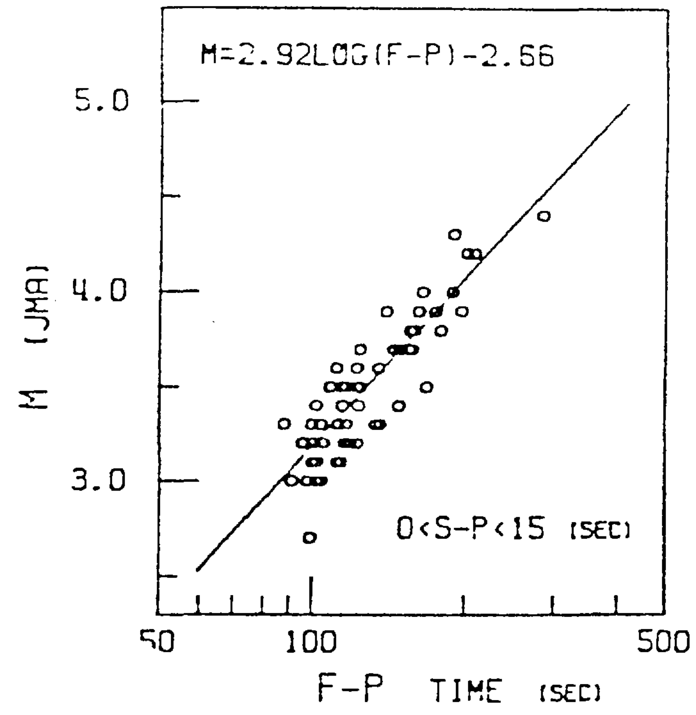


Fig. A-4 Relation between the total durations of oscillation (F-P) and the magnitudes determined by the Japan Meteorological Agency (J.M.A.).

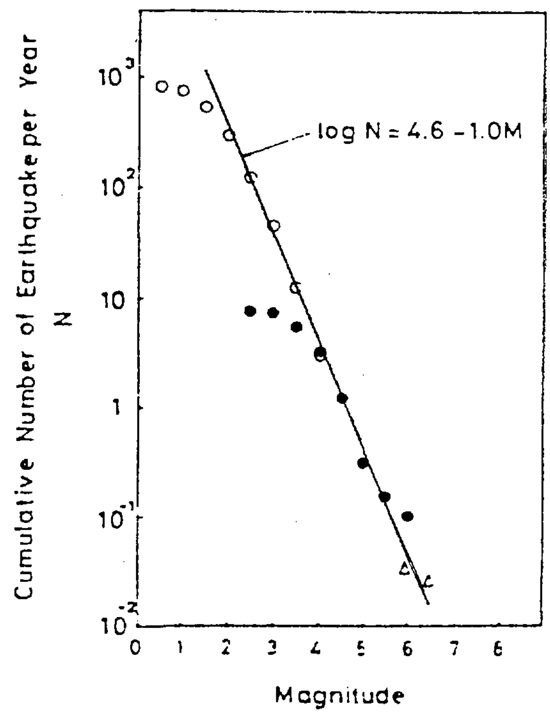


Fig. A-5 Relation between magnitude and cumulative number of earthquakes per year by using earthquake data detected by the Ikata network during 11/18/75 through 1/31/80 (open circles), those by J.M.A. during 1/1/61 through 1/31/80 (solid circles) and the major disastrous earthquakes since the late 16th century (open triangles)

APPENDIX B

Determination of Earthquake Magnitude

B.I. Magnitude Determination for Earthquakes in General

Magnitude is a measure of earthquake size or wave energy emitted from an earthquake source to be determined directly from instrumental observations. It should not be confused with intensity which is a measure of the effects of ground motion due to an earthquake at a particular site as inferred from human observations and judgement.

Local magnitude M_L, surface wave magnitude M_s, and body wave magnitude m_B are main types of magnitudes currently used. They are defined as follows:

(1) Local magnitude $M_L = \log A - \log A_o$,

where A is the maximum trace amplitude (mm) recorded on the Wood-Anderson torsion seismograph ($T_o = 0.8$s, $h = 0.8$, $V = 2800$) of the earthquake with magnitude M_L and A_o is that of the standard earthquake $M_L = 0$. In the above, T_o is the natural period of the instrument, h is the damping ratio and V is the amplification factor. A_o was given in a tabular form for $\Delta = 25 - 600$ km and as a function of $A_o = -3 \log \Delta + 3.37$ for $\Delta = 200 - 1000$ km [40] and in a table for $\Delta = 0 - 30$ km [41] for S. California earthquakes. This definition was applied also for several other regions but generally different calibration function A_o or equivalent function for the ground displacement should be given from the local observations of the respective regions.

(2) Surface wave magnitude $M_s = \log AH + 1.656 \log \Delta + 1.818$

where $AH = (AN^2 + AE^2)^{1/2}$, AN and AE being NS and EW components of maximum ground amplitudes of surface waves in (μm) with period around 20 s, for the epicentral distance $\Delta = 15^o - 130^o$ [42]. Standard formula now used internationally is:

$$M_s = \log (A/T) \max + 1.66 \log \Delta + 3.3$$

where:

A is the maximum ground amplitude of surface waves in (μm) with $T = 20 \pm 2$ s for $\Delta = 20^o - 160^o$ [43]

Since 1978 the vertical component AZ has been used instead of the vectorial sum of horizontal component $AH = (AN^2 + AE^2)^{1/2}$. For the earthquakes larger than magnitude 8, M_s sometimes does not correctly express the size or energy of earthquakes. In order to meet this phenomena or to prevent such saturation of M_s scale, Hanks and Kanamori [44] introduced M_W for the super-large earthquakes, based on the moment M_o (dyn.cm) of earthquakes as follows:

$$M_W = (2/3) \log M_o + 10.7$$

which is designed to be continuous at M_s around 8. The earthquake moment $M_o = \mu$ DS, where μ is rigidity (dyn/cm^2), D is the fault displacement (cm) and S is the area of fault moved (cm^2). M_w is often called "moment magnitude" or "Kanamori magnitude".

(3) Body wave magnitude $m_B = \log (A/T) + Q(\Delta, h)$

where A is the maximum ground amplitude of body wave groups in (μm), (P, PP, S), Q in (μm) with T = 4 - 10 (s) for $\Delta = 5^o$ and Q (Δ,h) is given in form of diagramns [45] and h is the focal depth in (km).

(4) Short period body wave magnitude $m_b = \log (A/T) + Q (\Delta,h)$

where A is the maximum ground amplitude of vertical component P wave group within several seconds from P on-set in (μm) with $T \leq 3$ s and $Q(\Delta, h)$ as given in [45]. Since early 1960s, m_b has been adopted as a standard magnitude routinely determined by the international centers, but it should not be confused with the body wave magnitude m_B, originally defined by Gutenberg and Richter, using medium period seismograph records.

A comprehensive earthquake catalogue [46] with magnitude M (often cited as M_{GR}), which is now understood as equivalent to M_s and many magnitude formulae for the different regions of the world have been established compatible with M_{GR}, e.g. $M = \log A + 1.62 \log \Delta^o + 1.97$ for the Strasbourg Station, $M = \log A + 1.73 \log \Delta - 0.83$ for the JMA network, etc. [47] where Δ is in km.

Magnitude compatible with M_{GR} has also been obtained by the duration of seismic records and by intensity distribution [48]. The duration magnitude M_D is useful for the microearthquake observation and the intensity magnitude M_I is indispensable for the evaluation of historical earthquakes, both being crucial for the siting of nuclear power plants.

B.II Magnitude determination for microearthquakes

Earthquakes of magnitude less than 3 are generally called microearthquakes. the magnitude of a microearthquake is defined either by the maximum amplitude or by the duration of the seismographic records, similar to the magnitude of larger earthquake. For either case the microearthquake magnitude formula should be calibrated with earthquakes having magnitudes of 3 to 4, determined by the local or regional network. If there is no local or regional network, giving the magnitudes of larger earthquakes for the region, the international determination should be used for the absolute calibration of the microearthquake magnitude formula. However, if is necessary to wait rather a long time to accumulate the sufficient data then the microearthquake magnitude should be considered as a relative scale until the calibration is established. In general, relative accuracy and absolute accuracy of the local magnitude scale are quite different as the fossil stratigraphy can very accurately decide the sequence of the strata at one locality but cannot compare the time sequence of strata at different localities.

The duration magnitude M_D is more convenient than the amplitude magnitude for the microearthquake observation, because the large number of recorded earthquakes with many of them exceeding the dynamic range of the recorder. This makes the reading of the maximum amplitude impossible.

One example of each of these methods is given below for illustration purposes.

B.2.1 Amplitude Magnitude [49]

Determination of earthquake magnitude at regional distance in and near Japan.

$M = \log A + 2.31 \log R - 1.38$ $(R < 40$ km)
$M = 1.18 \log A_V + 2.04 \log R + 2.94$ R $(R < 200$ km)
A: maximum ground displacement amplitude (μm)
A_V: maximum ground velocity amplitude (kine)
R: hypocentral distance (km)
M: magnitude compatible with M_{JMA}

B.2.2 Duration magnitude [50]

A method of estimating magnitude of local earthquakes from signal duration.

$M_D = -0.87 + 2.00 \log \tau + 0.0035 \Delta$
τ : duration (s)
Δ : epicentral distance (km)
M_D : estimate of Richter magnitude M_L (for the Central California microearthquakes)

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LIST OF PARTICIPANTS, CONSULTANTS AND CONTRIBUTORS

Consultants Meeting on the Application of Microearthquake Survey in Nuclear Power Plant Siting, 29 November - 10 December 1982

France	B. Mohammadioun	Inst. de Surete Nucleaire
India	H.K. Gupta	Centre for Earth Sciences Studies
	R.D. Sharma	Bhabha Atomic Research Centre
Japan	S. Miyamura	International Inst. of Seismology and Earthquake Engineering
IAEA	E. Iansiti	Division of Nuclear Safety
	P. Giuliani	" " " "

Consultants Meeting on the Application of Microearthquake Survey in Nuclear Power Plant Siting, 14 - 18 November 1983

France	B. Mohammadioun	Inst. de Surete Nucleaire
India	R.D. Sharma	Bhabha Atomic Research Centre
Japan	S. Miyamura	International Inst. of Seismology and Earthquake Engineering
U.S.A.	E. Jackson	U.S. Nuclear Regulatory Commission
IAEA	E. Iansiti	Division of Nuclear Safety
	P. Giuliani	" " " "

Consultants Meeting on the Application of Microearthquake Survey in Nuclear Power Plant Siting, 25 February - 2 March 1985

Japan	M. Watabe	University of Tokyo Metropolitan

Scientific Secretary	A. Karbassioun,	Division of Nuclear Safety

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