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PLANNING MICROEARTHQUAKE INVESTIGATIONS IN REGIONS OF NUCLEAR POWER PLANT SITES

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ABSTRACT

In a selected region where in important structure such as nuclear power plant, high dam or a large industrial complex is planned, it is necessary to carry out systematic seismic investigations starting well before the construction phase and extending preferably over the whole operating life time of the plant. This paper highlights the importance of such investigations that are related to seismicity and seismotechtonic status of the region through acquisition of data of microearthquakes constituted by very small seismic signals of relatively low magnitude but high frequency of occurrence. The procedure for establishing small aperture telemetered microearthquake network interfaced to a centralized digital recording and data processing facility is described. A scheme is presented wherein the data generated by continuous regional seismic monitoring are analysed using estimates of source location, signal duration magnitude, b-value profile, power spectra, spatiotemporal changes in seismicity, local crustal structure and other pertinent parameters for seismotectonic assessment of the region.

INTRODUCTION

Microearthquakes are generally referred to as small earthquakes with local magnitude not exceeding 3. Such weak tremors have very low intensity levels at which ground vibrations produced by them are not felt by human beings nor is their strength adequate to cause any damage to surface structures. They can only be detected instrumentally by using sensitive seismic devices.

A regional group of several closely spaced highly sensitive seismic stations constitutes a microearthquake network. At present, more than 100 permanent microearthquake networks are in operation throughout the world, which generate large quantities of seismic data. These networks evolved essentially from temporary expeditions for studying aftershocks of large continental earthquakes. Since oceanic microearthquake studies have been much less extensive than those of continental earthquakes, most of the microseismic monitoring networks are land based. There are no such permanent seismic networks at sea, although a shallow water microearthquake net is operating off the coast of southern California (Heney et al., 1979; see also Phillips and McCowan, 1978, for a review of the current state of ocean bottom seismographic (OBS) system).

Microearthquake networks are well suited for studying seismically active areas. They are recognized as powerful tools for investigating in great detail the earthquake generating processes. The usefulness of microearthquake recordings in a given region, where a proposal to put up a nuclear power plant (NPP) or other such important large industrial complex is under consideration, is well known. For example, microearthquake data can render help in the following ways:

(a) To delineate potentially active geological faults which may not have perceptible surface expressions.

(b) To study the characteristics of zonal seismic sources and infer the dynamical properties of the source region.

(c) To evaluate attenuation function for seismic waves traversing the site and determine energy transfer function of the site.

(d) To supplement seismological information available from historical records and regional catalogues of earthquakes.

(e) To assess natural seismicity and the seismotectonic status of the province under investigation.

(f) To keep vigil on any abnormal regional seismic activity during the life time of the plant. Such surveillance is directly related to the safety aspect of the operating system.

(g) To identify (by analysing foreshock-aftershock pattern) induced seismicity due to secondary causes such as impoundment of a large dam reservoir, mining activity, fluid injection or withdrawal, underground explosions, etc. in the vicinity of the site.

Thus, collection of microearthquake data over an adequately large period of time is an important exercise that can provide valuable inputs for estimation of seismic hazard in a given area. The support it lends in matters related to design basis ground motion and other siting decisions is significant. In cases of vital installations such as NPP where safety is of prime consideration, the seismic monitoring time window should span from few years before the construction phase of the plant to the end of its operating life. This would generate an extensive microearthquake regional catalogue needed for checking the severity pattern of the earthquake occurrences in the region. It may be mentioned that absence of microseismicity or the lack of it over an extended period of time, which may support inference of a so-called spatiotemporal seismic gap (Mogi, 1979) or of a probably dormant fault, is an important result that warrants careful consideration in NPP siting problem.

Lee and Stewart (1981) have brought out a book in which general principles of microearthquake surveys and their applications with regard to various geophysical problems are discussed incorporating illustrations of such applications in some countries. More recently, IAEA (1985) has published a similar document dealing with specific application of microearthquake monitoring in NPP sites. In this paper we present general description reviewing the objectives and the methodology to organize microearthquake investigations in selected regions of importance such as NPP sites. More technical details of seismographic systems and data analysis procedures will be elaborated separately with special reference to particular sites under consideration for putting up industrial plants.

TYPICAL APPLICATIONS OF MICROEARTHQUAKE SURVEYS

Microearthquake survey at a chosen site should be started well before the construction phase of the plant, and it may continue even during the construction period. Seismic investigations at such a site using a permanent microearthquake network should, however, be carried out throughout the operating life of the plant as has been emphasized later in this paper.

Among numerous applications of microearthquake surveys, we summarize below their main applications highlighting the geophysical information they are expected to yield for a site. The time duration of such surveys should be sufficiently large (typically 3-5 years) to conclude a case study with reasonable level of confidence.

2.1 It provides confirmatory evidence regarding the presence (or the absence) of active geological fault that gives rise to microtremors. The depthwise extension of such a tectonic feature can be ascertained from the estimates of focal depth of the seismic sources. The fault plane geometry can be deduced from composite source mechanism solutions of the earthquakes associated with one and the same tectonic block (Wickens and Hodgson, 1967; Shapira and Bath, 1978). This leads to the determination of the extent and the nature of faulting including direction of strike and sense of slip.

2.2 The relationship governing microearthquake magnitude and frequency of occurrence (Gutenberg and Richter, 1954, 1956) provides a check on the recurrence time interval of the seismic activity in a given range of severity. A caution must, however, be exercised not to extrapolate such linear relationships over large magnitudes in an attempt to infer the return period of a large earthquake vis-a-vis the design basis earthquake or maximum earthquake potential of the seismogenic province.

2.3 The relative strength of signals obtained from the observed microseismograms helps to deduce seismic wave attenuation model in the region, which can be combined with strong motion data, if available, for that region.

2.4 The problem of "floating earthquake" (an earthquake which cannot be associated with any known lineament but is considered for the purpose of aseismic design a probable earthquake that is likely to occur anywhere within the region of interest) in the vicinity of a site under active consideration can easily be overcome by verifying through microearthquake survey as to whether there is any systematic pattern of microearthquakes in the neighbourhood of the epicentre of the floating earthquake. This can also provide an insight into a geologic structure capable of generating an earthquake. Such result has a bearing on the near-field design response spectrum.

2.5 A microearthquake survey, particularly the study of migration pattern of deep microseismic sources can assist in locating subducting zones whose knowledge would be useful in seismic design considerations.

2.6 Exploring for geothermal resources and investigating the structure of earth's crust and upper mantle are also important applications of microearthquakes studies.

ESTABLISHING A SEISMIC NETWORK FOR MICROEARTHQUAKE INVESTIGATIONS

For carrying out microearthquake investigations it is necessary to establish one or more (depending on the areal extent) permanent local seismic networks capable of generating continuously high quality (large signal to noise ratio) seismic data both in analog as well as digital form. To accomplish this task, the following steps are recommended (e.g., Arora et al., 1988, 1989):

3.1 **Reconnaissance survey :** With the help of detailed toposheets, road maps and other relevant maps of the region, a reconnaissance survey is conducted to examine the logistics, especially with regard to the items described below.

(a) Far away (preferably more than 100 km) from industrial belt, city traffic and airfield, the area around each of the planned field seismic stations should be free from all possible sources of cultural background seismic noise that interferes with detection of weak signals from small earthquakes. Besides, remoteness from railway line (about 10 km), from highways (about 5 km), from local water bodies and small village (about 3 km) and from human activity connected with agriculture (1-2) km would be ideal. Proximity of large trees should also be avoided to reduce the effect due to wind generated seismic noise. However, the sites should normally be accessible by jeep vehicle to facilitate routine maintenance of field stations.

(b) The field station sites should have unweathered rock or strata composed of reasonably well consolidated material at 1-2 meter depth where seismic sensors can be emplaced to achieve good coupling with basement rock. In regions of thick alluvial sediments, precast RCC pits should be employed for installation of sensors.

(c) Seismic data of chemical blasts and rockbursts contaminate those due to natural earthquakes. Hence, the areas of blasting activity at nearby quarries or construction projects, if any, should be identified to help in the discrimination of natural earthquakes from man made seismic events.

3.2 Line of sight survey : It is usually cumbersome to operate and maintain on continuous basis field seismic stations in remote localities that may also have rugged terrain where independent seismographs are installed. Moreover, such stations with separate timing systems often report signal arrival times which are internally inconsistent owing to differential timing errors. This results in large discrepancies in data analysis. Therefore, it is essential to organize centralized seismic monitoring on a common time base.

Secondly, connecting field stations by cables to a central recording laboratory (CRL) involves laying and maintenance of large lengths of special signal cables. This is not only expensive but it also poses innumerable difficulties in respect of trouble-free operation. Thus, in order to ensure uninterrupted functioning of the network, establishing ground based wireless communication links between field stations and CRL (radio telemetry) is preferred to cable telemetry. One can also examine the feasibility of making use of laser communication links which are more elegent than conventional wireless transmitters and receeivers. The laser telemetry system is, however, known to work satisfactorily over a small distance range up to few kilometers only. For larger distance coverage, one may have to set up laser repeater stations.

In view of the above requirement, a field survey has to be conducted using portable transreceiver sets to establish clear (unobstructed) line of sight between each likely field station and the proposed CRL (see, for example, Arora, 1985). Sometimes, a wireless repeater station has to be added if any obstruction in the line of sight communication is insurmountable. The site for master receiving station (MRS) near CRL should be chosen preferably at relatively elevated place to gain natural advantage of height. On the other hand, if MRS/CRL has to be sited in a valley, then it will be necessary to put up close to the central station a tall sturdy tower for efficient wireless communication minimizing fading of radio signals.

3.3 Mains power availability : It is recommended that all field stations should be driven by DC battery power considering that electrical load at these stations is very small (12 volt industrial type battery may last several weeks without recharging) and that the commercial power supply may not be easily available at remote places of such stations. However, the CRL containing major equipment has to have stable AC mains supply line with fluctuations in voltage and frequency, if any, within permissible limits.

3.4 Background noise measurements : To decide actual locations of seismometers in the proposed network, the level of background microseismic noise, particularly in the high frequency band (5-50 Hz), must be determined. In this respect, noise measurements should be made every day and for several days using a portable short period (1 sec) seismograph with digital magnetic tape recording. Ground noise should be adequately sampled at quiet and disturbed times of the day and the season to arrive at an estimate of the year round noise level in the frequency band of interest. A size with less than 5 nanometers peak displacement due to the noise at 10 Hz is considered to be a very quiet site. Such a site is ideal for a microearthquake monitoring station. It may be noted that the oceanic and storm microseisms of relatively longer period (1 sec and above) do not deteriorate the performance of a microearthquake recording station that usually operates in a passband whose lower cut off is at 5 Hz.

3.5 Microearthquake network design : We describe below the salient features of field and laboratory system of a sensitive local seismic network suitable for continuously monitoring microearthquake activity. It is based on the experience of USGS which installed a microearthquake network along the San Andreas fault system in central California for mapping microearthquakes in order to study the mechanics of earthquake generation there (Eaton, 1977). Designed to telemeter seismic signals from field stations to a recording and data processing centre in Menlo Park, California, the network grew to 250 stations by the year 1980.

3.5.1 Network aperature and number of sensors : Typically, the area enclosed by a network may be about 30 km by 30 km. Although observations from a minimum number of five field stations are required to locate seismic sources, it is better to deploy 10-15 sensors for redundancy and denser coverage. The geometry of the net can be finalized by computerized simulation of seismometer stations and hypothetical sources so as to get desired accuracy of location of seismic events within the outermost boundary of the net. Situated close to seismic sources, two or three stations constituting the inner net will provide a good control on focal depth determination.

3.5.2 Field instrumentation : The field seismic system comprises essentially a short period (1 or 2 natural frequency) vertical component seismometer installed on a concrete plinth at the base of a pit excavated through top soil to a depth of 1-2 meters and encased by a mild steel (clamshell) with water tight lid. The associated electronic units such as signal conditioner, frequency modulator (FM), lighting protector, etc. are also placed inside the clamshell. In an upgraded system with digital transmission and recording of seismic data (Hayman and Shannon, 1979) the digitizer (ADC) and automatic gain control (AGC) units will replace the FM sender (Jensen, 1976; Harjes and Seidl, 1978).

The sender output is fed to a transmitter which operates in preferably the UHF band (e.g., 430-470 MHz). The transmitter is housed inside a thermally insulated, water tight jacket mounted near the top of a mast which also carries a suitable antenna (corner reflector type or multielement Yagi).

The field electronic units are powered by a 12 volt DC battery placed near the seismometer pit. Through a charge regulator, the battery is trickle charged by a 16-32 watt solar power panel which is also mounted atop the antenna mast. The solar panel has to be periodically cleaned with the help of a soft moist linen to wipe off the dust that lowers the photovoltaic efficiency of the solar cells.

For detecting predominantly horizotal ground motion at small distance from the earthquake sources, especially that due to shear waves, the stations in the inner part of the network should have 3-component seismometer modules. In such a case the outputs from the three transducers can be mixed using, for example, frequency division multiplexing (FDM) technique and then transmitted to CRL over a single carrier frequency.

To further suppress the high frequency cultural microseismic noise, installation of sensors at 50-100 meter depths inside boreholes is suggested. This would allow enhanced operational magnification of the network, which is necessary for detection of weak micrometer signals.

It would be preferable to provide some barbed wire fencing around each of the field stations for protection against human and animal vandalism.

3.5.3 Central laboratory instrumentation : The CRL can be configured in a number of ways depending on the requirements it has to fulfil. The basic CRL design, however, consists of a master receiving station (MRS) that collects through receiving antennas and well tuned UHF receivers all signals from the remote field stations. These signals are routed through discriminator and suitable coder circuitry to multichannel digital tape recording system acquiring data at the rate of 200 samples per second per channel. A time channel of coded time pulses derived from a crystal controlled stable electronic clock (stability better than 1 in 10^7), synchronized with standard time transmission, is also registered along with seismic signals. Two or three single-channel helical drum recorders are used to visually monitor preselected field channels to keep a check on the operational status of such channels besides obtaining a 24-hourly compact seismic record that helps in editing the tape during data retrieval.

The tape reply facility has decoder and multichannel oscillographic paper chart recorder which provides transcripts of tape recorded signals at preset chart speed and playout sensitivity.

The main recording system can be organized either in continuous recording mode (all signals and noise are recorded continuously) or in interrupt mode (only machine recognized signals satisfying STA/LTA detection criterion are recorded), which is the same as triggered recording suggested by Teng et al. (1973). Similarly, the replay system can be operated in either on-line trigger mode or off-line mode as may be necessary.

The data acquisition and handling system may be further automated by interfacing it to a suitable computing system built around a standard PC-XT/AT microprocessor for preliminary processing and archiving of data. Several automated data processing systems for microearthquake nets have been reported (e.g., Crampin and Fyfe, 1974; Stewart, 1977). There are, however, some limitations of such systems, although they appear very attractive to use. The main problem arises out of the difficulty in distinguishing between seismic onsets and nonseismic transients. The complexity of microearthquake signals poses considerable difficulty in designing computer programs for machine processing large volume of seismic data. The role of a geophysicist becomes increasingly important at this juncture.

The CRL requires AC mains supply to power various units there. It is, however, necessary to provide UPS (uninterrupted power supply) back up of appropriate rating to keep at least the recording system continuously operational even during mains failures. Alternatively, one may set up a battery bank with inverter to drive the vital equipment at CRL.

The entire system should be periodically calibrated to check its characteristics. Ideally, the dynamic range of the overall seismic monitoring system should be 100 db or more to allow recording of small earthquakes over a reasonably large range of magnitude (e.g., up to 4). This can be achieved by upgrading the analog field stations to digital stations equipped with 16 bit ADC and using gain ranging technique (Jensen, 1976).

DATA ANALYSIS

The analog as well as the digital records of microearthquakes have to be processed to extract various parameters, among which the prominent ones are as follows:

4.1 Hypocentral location : The epicentral location and, more importantly, the source depth can be determined using arrival times of P and S signals together with the knowledge of the velocity-depth structure in the regional crust. Standard computer routines, for instance, HYPO71 by Lee and Lahr (1975; Lahr, 1979) are available for such determinations.

Recently, we developed a computer program HYPOGEL and tested it on a large number of Koyna earthquakes (Arora and Krishnan, 1988), which computes hypocentral solution along with a typical velocity function that combines mean velocities of both P and S waves in the upper crust. The quality of hypocentral determination is judged by the stability of this typical velocity function and, of course, the standard deviation of time residuals. The algorithm requires data of S-P intervals from at least five local stations. In such a case, it does not have to depend on any layered crustal structure model since it is intended to be applied to a small aperture network where seismic waves are confined more or less to the upper crustal section having small variation in the velocity of these waves. Nevertheless, if crustal structure and regional travel times are accurately known, these can be used as additional inputs in the program. The focal depth computation relies only on the near-field data (i.e., data from stations whose epicentral distances happen to be smaller than the least distance from the preliminary hypocentre). Besides, the program incorporates several input options such as most and/or least reliable data in a set, probable unrelated arrival, etc.

For accurate source location, however, precise geographic coordinates of stations with elevations from ground datum as well as signal onsets identified from seismograms with adequate time resolution are necessary. The estimate of origin time of a microearthquake is less important, especially in seismicity studies. If required, however, it can be easily calculated from Wadati diagrams where S-P intervals are plotted as a function of P arrival times.

Systematic reading errors in picking out onset times are not serious as they only lead to proportionate shifts in the origin time of an event without influencing its hypocentral location. But, random arrival time errors result in source mislocation and, besides, they are difficult to be removed from the data. To evaluate the effect of such random errors in the input data corresponding to a given network, special analytical studies are needed (Arora et al., 1980; Arora and Krishnan, 1988).

4.2 Magnitude : The coda duration of signals in a seismic record can be exploited for estimating magnitude of a microearthquake (Lee et al., 1972). Different ways have been suggested to measure the record duration, but the one most commonly used in to measure the time interval between the onset and the end of record where the last arriving signal just merges in the prevailing background noise (signal amplitude equals noise amplitude).

A large number of duration magnitude formulae have been worked out by many investigators depending on region, nature of instrument used for recording signals and range of epicentral distance involved (Bath, 1981). A general expression for coda duration magnitude (M_τ) is of the form:

$$M_\tau = a_1 \log\tau + a_2(\log\tau)^2 + a_3\Delta + a_4 d + a_5 \qquad (1)$$

where τ is coda duration usually in seconds, Δ and d are epicentral distance and focal depth respectively, usually both expressed in kilometers, and a_1 to a_5 are some constants.

In several case studies, the contribution from the nonlinear term containing $(\log\tau)^2$ is found to be negligible in the smaller distance range ($\Delta < 100$ km). Also, for regional seismic events, the distance and depth dependence on coda duration is generally small. It is so because compression along the length of seismic record due to signal attenuation at an increased hypocentral distance is compensated by enhancement in separation of S signal from the corresponding P signal at that distance. Thus, quite often, distance and depth dependent terms are safely neglected, which yields a duration-magnitude relation that simply reduces to the form (e.g., Talwani et al., 1979):

$$M_\tau = a \log\tau + b \qquad (2)$$

For every given region, such a relationship will have to be deduced by regression analysis of a sufficiently large set of earthquake data. For example, in Bhatsa region about 100 km northeast of Bombay, we use the following relation, for shallow-focus sources ($d < 20$ km) and $M_\tau < 4.5$:

$$M_\tau = 2.26 \log\tau - 1.71 \qquad (3)$$

The expression (3) is formulated by employing the average values of the empirical constants suggested by various workers in a number of coda duration magnitude relations in hard rock regions of the world, listed out by Bath (1981). This relationship (3) is under further scrutiny using regional seismic data from the Bhatsa radio telemetered seismic network that became operational in April, 1988 (Arora et al., 1988).

A slightly modified relation involving some change in the values of the constants has been used by us to assign magnitudes to small earthquakes detected by our Delhi seismic tripartite network within about 200 km from Delhi. It is, however, noted that, by adopting a somewhat different expression for magnitude, the data interpretation and analysis do not suffer from any adverse effects so long as the purpose of magnitude estimation of small local earthquakes is to account for relative strength of the sources (internal grading of events).

4.3 b-values : The slope given by b-value in the Gutenberg-Richter magnitude-frequency (recurrence) relation should be estimated using a large number of microearthquakes recorded over an extended period of time. These estimates can be made using least squares approach. Utsu (1965) has proposed for estimating the constant b an alternative method in which magnitude values alone (minimum or threshold magnitude, M_{min}, and average magnitude, M) are considered in an extensive earthquake catalogue. This is known as the maximum likelihood method. Some workers (Knopoff and Kagan, 1977; Weichert and Milne, 1979; Weichert, 1980) have preferred the maximum likelihood method to the least squares method.

Block b-value (e.g., in a yearly or 5-yearly time block) should be compared with the profile of b-values obtained by sliding a time window of small length (e.g., one month) along the time axis of the piece of data. This parameter can help in checking the severity of the design basis ground motion evaluated independently besides contributing significantly to the understanding of the regional seismicity pattern.

A caution must, however, be exercised in the above analysis by avoiding mix up of regional data due to any swarms of aftershocks that usually follow a moderate earthquake. Histograms of microearthquake count per unit time generally help in drawing conclusions regarding seismicity.

4.4 Spectra : Microearthquake digital seismograms of P and S waves obtained with a least 200 samples per second per channel should be subjected to spectral analysis. Fast fourier transform (FFT; Cooley et al., 1967; Bath, 1974) and auto regression (AR: Ulrych and Bishop, 1975; Ulrych and Clayton, 1976) techniques are well suited for such analysis. It enables estimation of power spectral density, corner frequency (from wide band records), Q-values (absorption) and some source parameters characteristic of the seismic region.

4.5 Crustal structure : Velocity-depth structure of the layered crust in the region where seismic network is established should be determined. Seismic sounding by means of controlled small chemical explosions conducted along several profiles traversing the region is best suited for such an exercise. The knowledge of crustal structure and regional travel times of P and S waves would largely improve source location.

4.6 Spatiotemporal changes in microseismicity : It is useful to examine space-time variation pattern of the microearthquake activity in the region of investigation over a reasonably large period of time. Any migration of earthquake foci in space points to activation of neotectonic lineaments in the neighbourhood of the known fault under monitoring. The change in the rate of occurrence of microearthquakes is another interesting parameter that relates to probable future seismicity and could also reveal the presence of new seismotectonic structures.

4.7 Integration with geologic and geophysical data : The interpretations associated with the analysis of microearthquake data should be combined with the available geologic information, particularly that on neotectonicity. Satellite imageries (remote sensing data) checked for their ground truths should be projected on the map showing distribution of microearthquakes to verify potential lineaments. Geophysical data such as basement topography, gravity anomalies, magnetic anomalies, electrical resistivity, heat flow, radon anomalies, etc. may also be examined to find correlation, if any, with the observed seismic activity. Such geophysical investigations may be useful particularly during the period of microearthquake survey in the preconstruction stage.

Coseismic measurements, of which those pertaining to geodetic parameters such as strain, ground tilt and crustal uplift are the most important ones, should be made periodically. These measurements should be included in the schedule of seismic investigations in the region of interest. Use of laser techniques for geodetic measurements is preferred to conventional geodimetry. Such modern techniques are already in vogue in many seismically active regions of the world.

CONCLUSIONS

The main conclusions are as follows :

(a) Microearthquake investigations in regions of important structures such as nuclear power plants, high dams, etc., are necessary for comprehensive assessment of seismicity, seismic risk and seismotectonics of a region. These investigations should be started in the preconstruction stage and continued preferably over the whole life time of the plant.

(b) A sensitive telemetered seismic network comprising 10-15 sensors in an area of about 30 km by 30 km should be established in the region of investigation. The network in continuous monitoring mode has to have centralized digital recording interfaced to a system for data transcription, processing and archiving.

(c) Analysis of seismic data obtained from the telenet involves a host of parameters such as source location, coda length and magnitude, migration pattern of seismicity, regional velocity-depth structure, temporal changes in b-value, spectral features of waveform and integration with geologic and geophysical data.

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