MAUSAM, **56**, 2 (April 2005), 465-472

550.34.044(540)

Configuration of an optimum seismological network for India

S. K. SRIVASTAV, RAJESH PRAKASH, R. S. DATTATRAYAM, S. K. ARORA*, B. K. BANSAL**

and

S. N. BHATTACHARYA***

India Meteorological Department, Lodi Road, New Delhi, India

**1, Shivam, Plot 121, Sector 28, Vashi, Navi Mumbai, India*

***Department of Science & Technology, New Delhi, India*

****Department of Geology & Geophysics, IIT, Kharagpur, India*

(*Received 12 March 2004*)

सार – भारत मौसम विज्ञान विभाग, (आई.एम.डी.) भारत सरकार का मुख्य अभिकरण है जो देश में तथा इसके आस–पास के स्थानों पर भूकम्पनीयता का मॉनीटरन करता है। भारत मौसम विज्ञान विभाग विशेष अध्ययनों के लिए उत्तरी भारत की कुछ वेधशालाओं के अतिरिक्त 47 स्थायी वेधशालाओं वाले राष्ट्रीय भूकंप विज्ञान संजाल का रख–रखाव करता है। दिल्ली और इसके आस–पास के स्थानों में भूकम्पनीयता का सही मॉनीटरन करने के लिए 16 मुख्य तत्वों वाले वी. एस. ए. टी. पर आधारित अंकीय दूरमिति प्रणाली भी कार्य कर रही है। भारत मौसम विज्ञान विभाग के अतिरिक्त अनेक राज्य/केन्द्र सरकार के संगठन, विश्वविद्यालय और अनुसंधान तथा विकास संस्थान भी देश के कई भागों में भूकम्प वैज्ञानिक वेधशालाएँ चला रहे हैं। 10 नए अंकीय विस्तृत बैंड वाले केन्द्र खोलने के अलावा प्रायद्वीपीय क्षेत्रों में स्थित वेधशालाओं में से कुछ को हाल ही में अति आधुनिक अंकीय विस्तृत बैंड भूकम्पलेखी प्रणालियों से उन्नत किया गया है। इस शोध–पत्र में भारत मौसम विज्ञान विभाग के मौजूदा संजाल से देश के किसी भी स्थान पर आने वाले भूकम्पों का नियमित रूप से पता लगाने और उनका स्थान निर्धारित करने की अधिकतम क्षमता का पता लगाने का प्रयास किया गया है। हिमालय और प्रायद्वीपीय क्षेत्रों में भूकम्पी तरंगों को कमज़ोर करने वाले अभिलक्षणों का उपयोग करते हुए हमने, उस अधिकेन्द्रीय दूरी का अनुमान लगाया है जहां से निश्चित परिमाण के क्षेत्रीय भूकम्प के स्थान के निर्धारण के अलावा भूकम्प का भी पता लगाया जा सकता है। समरूपी दिगंशीय प्रसारण क्षेत्र और अवकेन्द्रीय प्राचलों का सही रूप से पता लगाने के लिए न्यूनतम संख्या में वेधशालाएँ खोलने पर भी विचार किया गया है। उपर्युक्त सूचनाओं पर आधारित अनुकूलतम भूकम्प वैज्ञानिक संजाल विन्यास तैयार किया गया है। इस विश्लेषण से यह पता चला है कि भारत मौसम विज्ञान विभाग के मौजूदा संजाल में राजस्थान, गुजरात, अरूणाचल प्रदेश तथा जम्मू और कश्मीर के कुछ क्षेत्रों को छोड़कर देश के मुख्य भागों में 3.5 और इससे भी अधिक परिमाण पर आने वाले भूकम्पों का पता लगाने और भूकम्प का स्थान निर्धारित करने की क्षमता है। इसमें यह भी बताने का प्रयास किया गया है कि क्षेत्रीय भूकम्प मॉनीटरन क्षमता से वेधशालाओं की कमी वाले क्षेत्रों में कई नई वेधशालाएँ स्थापित करने के साथ–साथ विभिन्न अन्य अभिकरणों द्वारा चलाई जा रही मौजूदा भूकम्प वैज्ञानिक वेधशालाओं के समुचित उन्नयन और समाकलन से अत्याधिक सुधार होगा।

ABSTRACT. India Meteorological Department (IMD) is the nodal agency of Government of India responsible for monitoring seismicity in and around the country. IMD maintains the national seismological network consisting of 47 permanent observatories, in addition to some observatories in northern India for special studies. A 16-element VSAT-based digital telemetry system for close monitoring of seismicity in and around Delhi is also in operation. In addition to IMD, several state/central government organizations, universities and R&D institutions are also operating seismological observatories in various parts of the country. Some of these observatories in the Peninsular shield region have been upgraded in the recent past with state-of-the-art digital broadband seismograph systems, in addition to opening 10 such new digital broadband stations. This paper makes an attempt to assess the magnitude threshold of routinely detecting and locating earthquakes occurring any where in the country with the existing IMD network. Using the seismic wave attenuation characteristics in the Himalayan and Peninsular shield regions, we have estimated epicentral distance up to which a regional earthquake of given magnitude can be detected and located as well. The minimum number of observatories required for uniform azimuthal coverage and accurate determination of hypocentral parameters has also been taken into consideration. An optimum seismological network configuration has been worked out based on the above inputs. It is found from the analysis that the existing IMD network is capable of detecting and locating earthquakes of magnitude 3.5 and above occurring in the mainland of the country, except for a few pockets in Rajasthan, Gujarat, Arunanchal Pradesh and J&K. An attempt has also been made to show that regional earthquake monitoring capability would largely improve by suitably upgrading and integrating the existing seismological observatories operated by various other agencies together with setting up a number of new observatories in the instrumental gap areas.

Key words – Optimum design network, Earthquake monitoring, Detection capability, VSAT.

1. Introduction

The first seismological observatory was set up by India Meteorological Department (IMD) at Kolkata in 1898. By independence (1947), only five seismological observatories were in operation at Calcutta, Bombay, Kodaikanal, Hyderabad and Delhi. Thereafter, the number of observatories under National Network increased steadily to the present figure of 47. Apart from these seismological observatories maintained under the national seismological network spread over the country, IMD also operates some seismological observatories in north India for special studies. A 16-element V-SAT (Very Small Aperture Terminal) based telemetry system has been installed to monitor the seismicity in and around Delhi region.

In the mid-60s, many other institutions also started operating seismological observatories for their own specific purposes. At present, as many as 150 seismological observatories are being operated outside the IMD network by Bhabha Atomic Research Centre (BARC), National Geophysical Research Institute (NGRI), Hyderabad, various State governments, River Valley projects, Universities and other R&D institutions (Bhattacharya and Dattatrayam, 2000). Sometimes, observatories are set up for short periods for time-bound projects and then closed down (Fig. 1 and Table 1).

In the wake of the Latur earthquake of 30 September, 1993 IMD took up a program of systematic upgradation of its seismological network and has since deployed state-of-the-art digital broadband seismograph systems at 24 observatories. Another 10 new observatories have also been established in Peninsular India by different organisations with similar state-of-the-art digital broadband seismographs. A National Seismological Database Center (NSDC) has been established at IMD, New Delhi, with necessary hardware and software to cater to the needs of near real time and offline data transfer, analysis and dissemination of earthquake products to various users. A block diagram showing the structure of NSDC is given in Fig. 2.

2. Structure of the present national seismological network

Fig. 1 illustrates the distribution of the existing seismological observatories where spatial gaps, non-uniform and large in certain areas, are evident. On the other hand, it may be seen that the stations at several places are operated quite close to each other rendering the network density rather uneven from region to region. Such a countrywide network is not adequate for detection of small earthquakes, down to magnitude 3.0, uniformly over

TABLE 1

Distribution of seismological observatories in India under different organizations

Organisation	Abbreviations	*No. of stations
India Meteorological Department	IMD	51
Wadia Institute of Himalayan Geology	WIHG	11
National Geophysical Research Institute	NGRI	20
Regional Research Laboratory,	Jorhat RRLJ	10
Bhaba Atomic Research Centre	BARC	2
Indian Institute of Geomagnetism	IIG	2
Geological Survey of India	GSI	1
National Institute of Rock Mechnics	NIRM	1
Central Scientific Instruments Organisation	CSIO	1
Centre for Earth Science Studies	CESS	1
	Subtotal	**100**
Maharashtra Engineering Research Institute	MERI	31
Gujrat Engineering Research Institute	GERI	17
Sardar Srovar Narmada Nigam Ltd.	SSNN	9
Narmada Valley Development Authority	NVDA	10
Kerala State Electricity Board	KSEB	12
	Subtotal	**79**
Guru Nanak Deb University, Amritsar	GNB Univ.	3
Delhi University	D. Univ.	3
University of Roorkee	UOR	9
Osmania University	O. Univ.	1
Manipur University	M. Univ.	4
Indian School of Mines, Dhanbad	ISM	1
Kumaun University	Kum.Univ.	5
Kurukshetra University	Kur. Univ.	1
	Subtotal	**27**
	Grand Total	206

*For information on latest position of no. of observatories, the concerned organisation may be contacted.

the entire country, and indeed nebulous for precise location of their sources. The existing seismic stations, having been set up by different organisations for different applications, do not have identical instrumentation or data recording facilities. This results in a large variation in the quality of data, both waveform and extracted parameters, which makes real-time seismic monitoring difficult. Besides, the unique geographical disposition of the Indian landmass, with the peninsula surrounded by the ocean from three sides, and rugged Himalayan mountain ranges in the north, inhibits proper azimuthal coverage of observing land stations.

The issue of magnitude threshold of locating earthquakes and the efficacy of the existing national seismological network has been debated time and again by several committees (Tandon Committee, 1971; Chaudhry Committee, 1986; Arya Committee, 1987 etc.,) and the consensus view is that there is a need to strengthen and upgrade the existing seismological network with state-of-the-art equipment in a phased manner to improve the

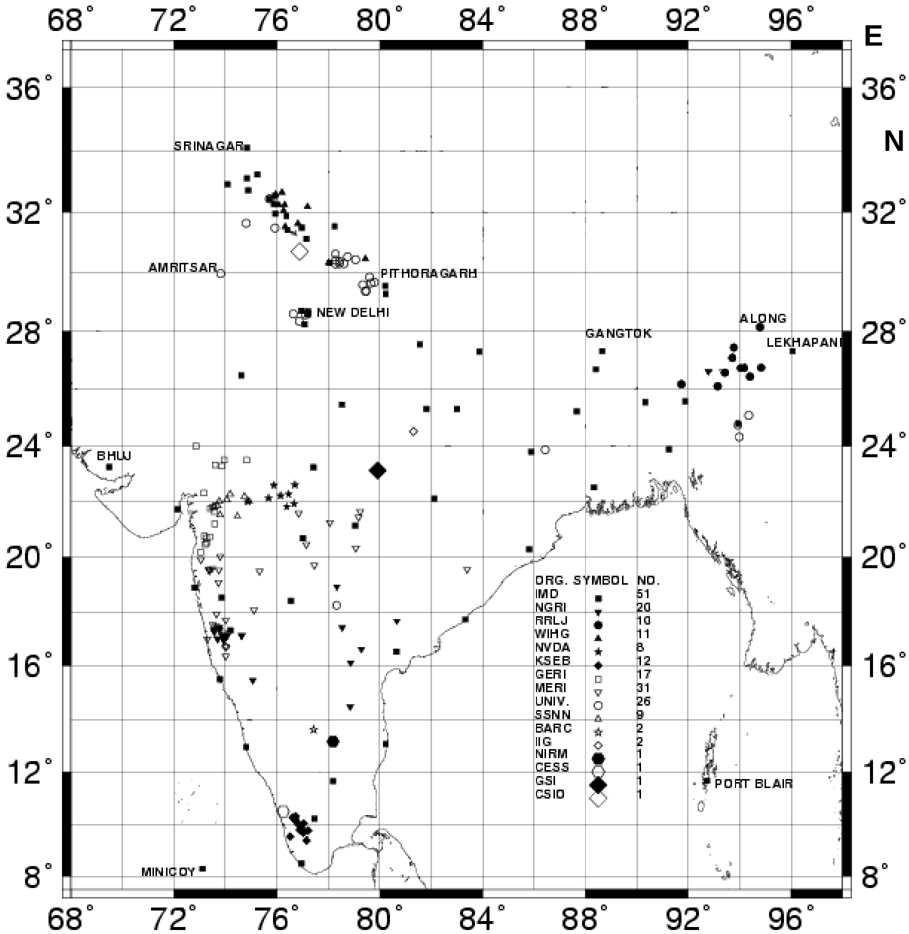

Fig. 1. Seismological Observatories in India

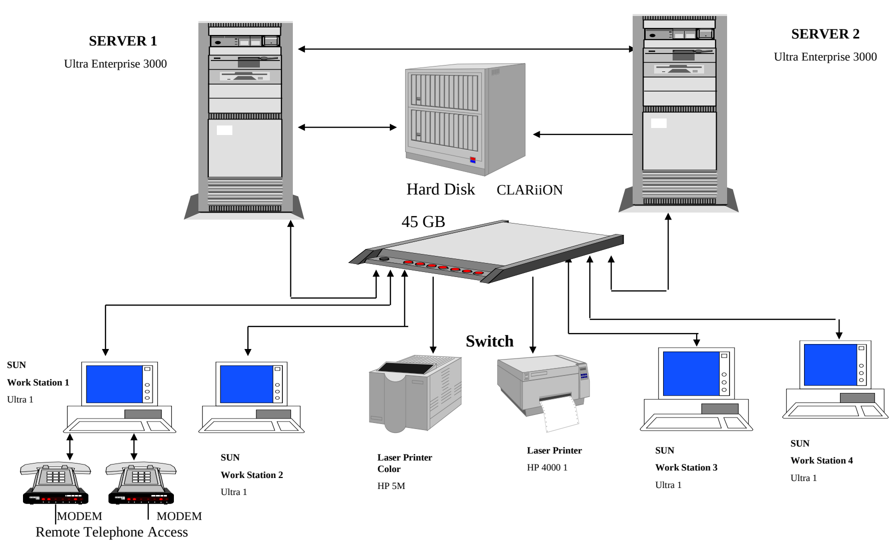

Fig. 2. Block diagram showing the structure of National Seismological Database Centre

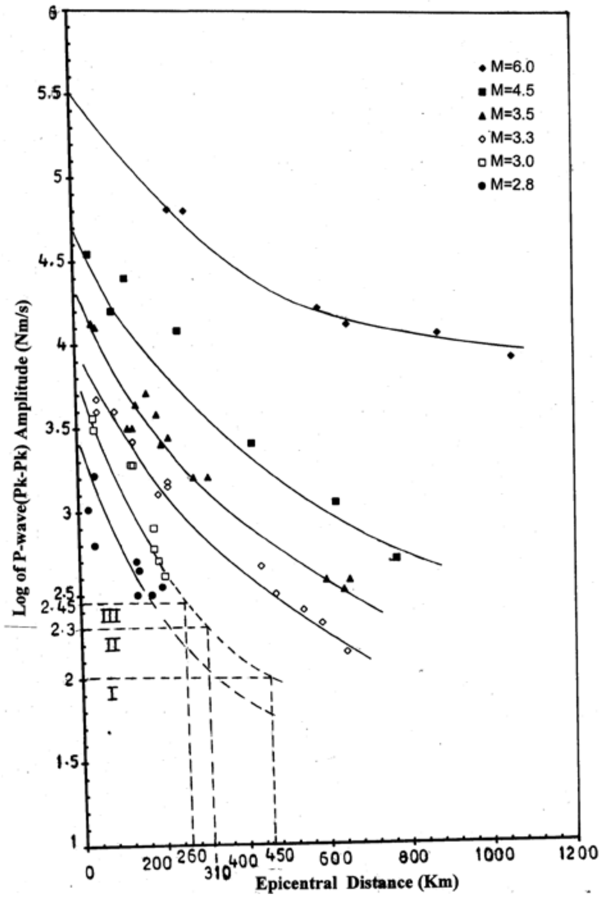

Fig. 3. P-wave attenuation for the peninsular region. Dashed lines I, II and III represent the logarithm of twice the ground noise amplitude (peak-to-peak in Nm/s) respectively from minimum, average and maximum levels at various distances of seismic stations in Peninsular region

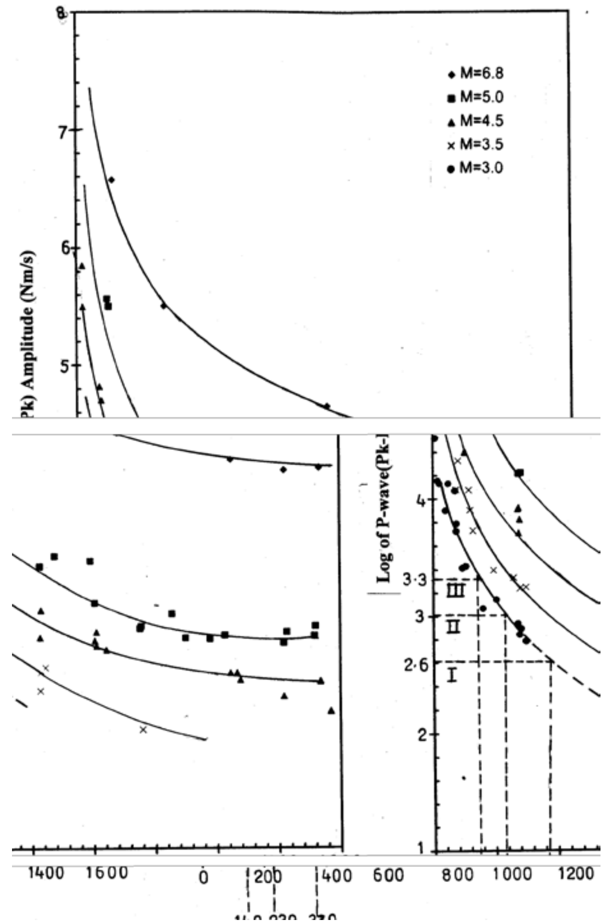

Fig. 4. P-wave attenuation for the Himalayan region. Dashed lines I, II and III represent the logarithm of twice the ground noise amplitude (peak-to-peak in Nm/s) respectively from minimum, average and maximum levels at various distances of seismic stations in Himalayan region

detection and location capabilities. Thus, there is an urgent need not only to strengthen the network but also to standardize the existing seismological observatories in the country to maintain uniformity in observational practices, data formatting and analysis. The existing infrastructure, manpower and resources in the country could then be utilized optimally and effectively. This is also expected to provide a major thrust to seismological research in the country, as the seismic data will be available on a broader platform to the scientific community.

3. Design of an optimum seismological network

3.1. *General requirements*

Consistent with the objectives mentioned above, an attempt has been made in this paper to design an optimum seismological network capable of detecting unambiguously and locating with uniform precision, all seismic events down to magnitude 3.0 occurring within the main landmass of the country (IMD Report, 1999, 2000). A two-pronged approach has been followed for this purpose. The first approach is based on practical aspects of network design, such as locations of the existing stations and the type of instrumentation available and the current status of knowledge of geotectonic features. The second approach uses a theoretical simulation of the network response to earthquake events. The theoretical simulation approach is more objective than the first. However, both the approaches have a common requirement that we should first know the range of epicentral distance to which the P-wave signal from an event can be detected unambiguously above the background noise. This involves a theoretical modelling of the P-wave attenuation process. When integrated with such an attenuation model, the two approaches tend to converge to an optimum configuration of stations.

Another important requirement arises from the obvious advantage of siting stations as closely as possible to known geological faults for improved detection and focal depth estimation. Finally, all the stations of the optimized network should ideally be equipped with identical state-of-the art triaxial broadband digital seismic equipment with most modern communication facilities for near real time data access. Stations that do not currently meet this advanced technology standards will have to be upgraded appropriately.

3.2. *P-wave attenuation modelling*

The maximum epicentral distance (Δ) at which a P-wave signal can be detected unambiguously above the background noise is the basic guiding factor in determining the maximum permissible spacing between two neighboring observatory stations. It is only to be expected that Δ will be different in the two distinct tectonic environments of our country prevailing in the Himalayan and Peninsular shield regions. The P-wave attenuation characteristics were therefore worked out separately for these two regions. For the Peninsular region, a data set was built up for 34 earthquake events with magnitudes ranging from 2.8 to 6.0. For the Himalayan region, the data set consisted of 40 earthquake events with magnitudes between 3.0 and 6.8.

The P-signal amplitudes corresponding to actual ground motion (particle velocity computed in nanometer/sec) recorded at different distances were obtained from the records of broadband digital stations operated by IMD. Since Δ is much larger than the focal depth (*d*) in each of these cases, the hypocentral distance (*R*) is closely equal to Δ as a first approximation. Hence, small variations in the value of *d* compared to *R* or Δ (*R*>> *d*) did not influence this study of signal attenuation with distance. In Fig. 3, we present the data of actual ground motion (peak-to-peak amplitudes of the observed P-signal) as a function of Δ for six different magnitudes from 2.8 to 6.0. The data are fitted through trend exponential curves, which turn out to be nearly parallel. The curve for Jabalpur earthquake of M 6.0 (topmost curve of Fig. 3), however, exhibits a slightly different behaviour. It evidently necessitates to employ a much larger data set, particularly at larger distances, to examine the true behaviour through the full range of magnitude and to smooth out any scatter therein. On the whole, the present attenuation trends seem to be in a reasonably good agreement internally regardless of the event magnitude. Apart from this, the maximum peak-to-peak amplitude of background noise was also measured for the participating stations. Each of the three dashed lines drawn across the amplitude axis in Fig. 3 represent twice the noise level at SNR (signal-to-noise ratio) of 2 corresponding to maximum, average and minimum values respectively. Assuming that P-wave is well discernible at a station only if the signal is twice the noise, the value of distance at the intersection of noise amplitude line and a curve of given magnitude shows the epicentral distance up to which an earthquake of that magnitude is recorded by an observatory. The data in Fig. 3 reveals that an earthquake of magnitude 3.0 will clearly be recorded on an average up to a distance of 310 km. An extrapolation of the decay curve for M3.5 would suggest that an earthquake of M 3.5 would be recorded up to a distance of nearly 770 km in the Peninsular region.

For the Himalayan region, the P-signal amplitudes corresponding to actual ground motion (particle velocity in nanometer/sec) were obtained from the records of short-period and broadband digital stations of IMD and from short-period digital stations in and around Chamoli, Uttaranchal. The data from the broadband digital stations of University of Roorkee at Narendranagar, was also used in the analysis. Fig. 4 gives the actual ground velocity (peak-to-peak amplitude of the observed P-signal) as a function of Δ for 5 different magnitudes from 3.0 to 6.8. The data are trend fitted with exponential curves which are found to be nearly parallel, a feature similar to the one obtained in the Peninsular shield. Like in Fig. 3, the horizontal dashed lines are drawn at twice the noise level (peak-to-peak amplitude of noise; SNR=2) corresponding to maximum, average and minimum values. Following the same procedure that has been adopted for the Peninsular region, it is inferred from Fig. 4 that an earthquake of magnitude 3.0 will clearly be recorded on an average up to a distance of 230 km in the Himalayan region. Similarly, we can infer from Fig. 4 that an earthquake of magnitude 3.5 will be clearly recorded up to a distance of about 390 km in the Himalayan region. Both these distances (230 km and 390 km) are considerably lower than those for Peninsular region (310 km and 770 km respectively) indicating a relatively larger and faster attenuation of P-waves in the Himalayas than in the Peninsular Shield.

3.3. *Theoretical approach*

For evaluating the performance of a given seismic network with regard to hypocentral location, several simulation exercises have been attempted in the past (Gupta *et al*., 1973; Arora *et al*., 1978, 1980; Bhattacharya *et al*., 1982). The approach used in this paper involves assuming a network geometry with a certain number of hypothetical stations, a seismic wave travel-time for a certain structure of layered earth and a source whose space and time coordinates are known. A set of arrival-time data is synthesized corresponding to the assumed source, which is then relocated using the well known source location program, HYPO 71 (Lee and Lahr, 1975) and the mislocation errors (spatial shift in the computed hypocentre with respect to the true hypocentre) determined for each typical network.

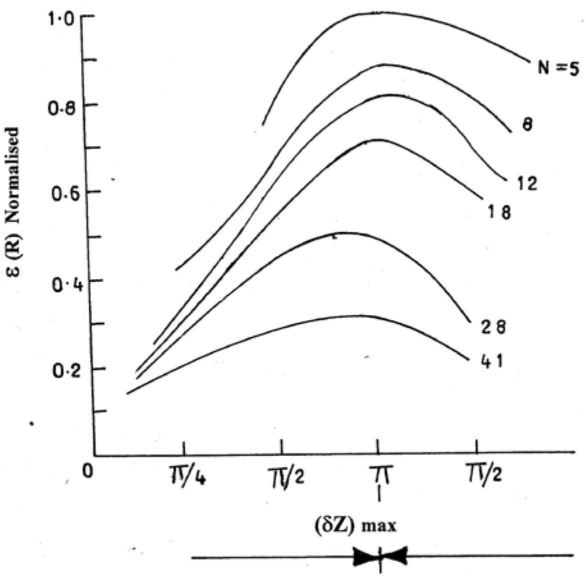

Fig.5. Mislocation error ε(R) *versus* maximum azimuthal gap (δZ) max giving hypocentral location response of simulated networks using synthetic arrival-time data. The azimuthal gap varies at different locations in the network area. The error is seen to be decreasing with the increase of number of recording stations (N)

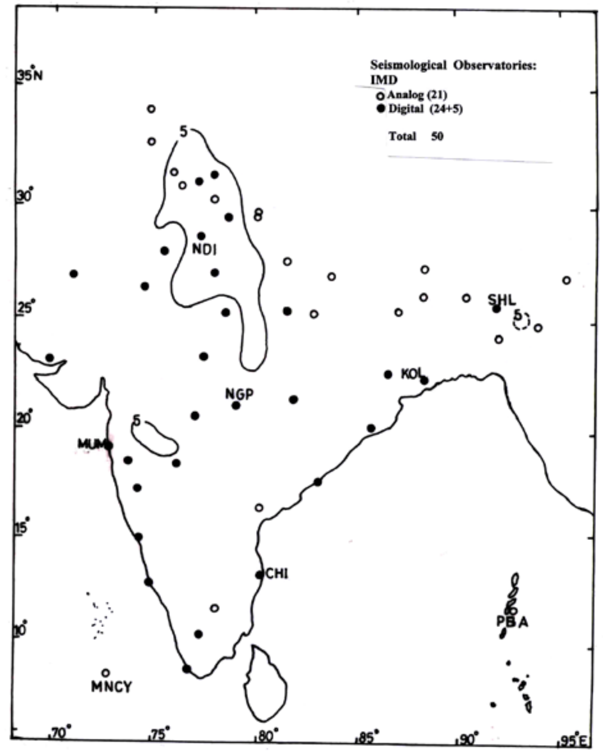

Fig. 6. Contours showing number of seismological observatories of the existing national network of IMD, recording earthquake of magnitude 3.0.

The mislocation errors were simulated for various networks designed with N number of stations randomly distributed in a typical circular area of 300 km radius. The network density was steadily increased from N = 5 to N = 41 and it also provided different azimuthal gaps whose role in evaluating network response is considered vital. An azimuthal gap (δZ) is the angle that a station pair subtends at the epicenter. Various such gaps could be realized by pulling the source towards the edge of the network. In the present case, the maximum azimuthal gap, $(\delta Z)_{max}$, varied from less than $\pi/6$ to π for all networks, beyond which the hypocentral solution turns unstable and, therefore, unreliable.

The results of this exercise are comprehensively illustrated through the family of curves presented in Fig. 5, where mislocation errors normalized to unity, $\in(R)$, are plotted against maximum azimuthal gap. As expected, $\in(R)$ progressively diminishes with increasing N and decreasing $(\delta Z)_{max}$ thereby indicating improvement in the network performance. Interestingly, it shows a saturation limit at N = 41 beyond which the network capability does not seem to improve noticeably.

3.4. *Practical approach*

In the practical approach, the main considerations are (*i*) locations of the existing stations and the type of instrumentation they have (*ii*) close proximity to faults/ lineaments which are known or probably exist and (*iii*) gaps in the network which require to be filled up. Using the results obtained from the attenuation study, an assessment has been made regarding the number of existing observatories, which will record an earthquake occurring at any given point on a 1° × 1° grid. As already mentioned, 47 seismological observatories are presently in operation in the national network of IMD. By integrating some of the observatories in operation under the VSAT based telemetry system of Delhi region, the total number of IMD observatories can be said to be 50. The results are shown in Fig. 6, considering these 50 stations, in the form of contour lines indicating the number of stations, which will record an event of M3.0 and above. Fig. 6 indicates that the present IMD network is not fully capable of recording earthquakes of M3.0. However, they can be located in regions such as Delhi, western Uttar Pradesh and parts of Haryana and Punjab. Similarly, Fig. 7 shows contours of the number of observatories recording an earthquake of magnitude 3.5. It is seen that with the present IMD network, earthquakes of magnitude 3.5 can be located almost the entire country except at some bordering regions of Rajasthan, Gujarat, Arunachal Pradesh and northern part of Jammu and Kashmir. It is to be borne in mind here that the results hold good assuming

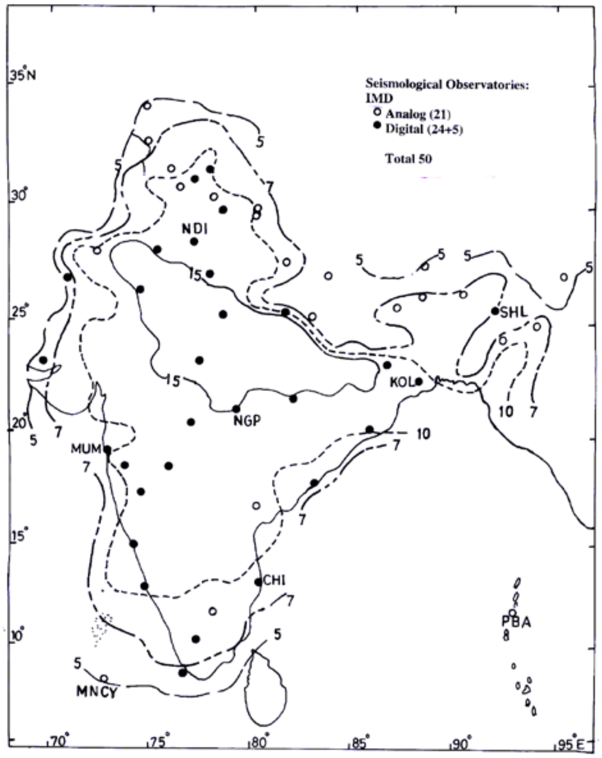

Fig. 7. Contours showing number of seismological observatories of the national network of IMD, recording earthquake of magnitude 3.5

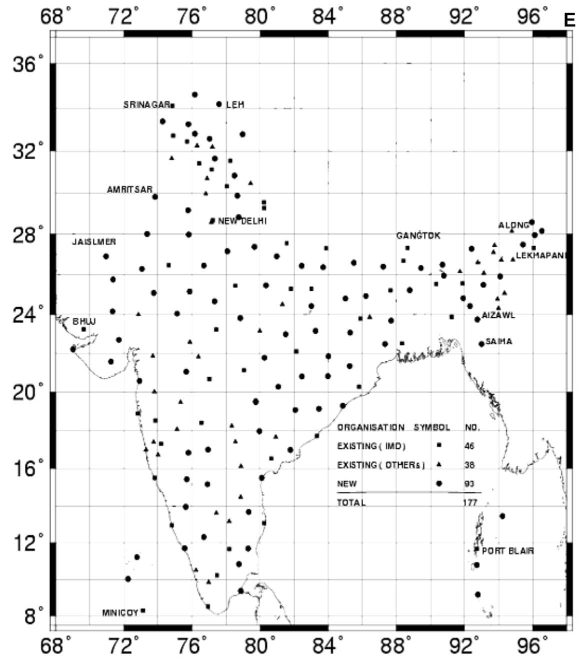

Fig. 8. Optimum seismological observatory network in India presently under development and deployment

that all the IMD stations are equipped to provide waveform data in real-time mode to the National Seismological Database Centre at Delhi. Currently, this is possible for only 29 out of the 50 stations. With these 29 observatories alone, earthquakes of magnitude 3.5 can be located only in small parts of northern India around Delhi and in Peninsular India. Thus, it is essential to upgrade the remaining 21 analog observatories with digital seismographs and matching communication facilities to achieve the location capability for M3.5 earthquakes in India in operational mode.

To meet the target of countrywide monitoring of M3.0 earthquakes, the 50-element network of IMD would not suffice. The requirements of such a network are depicted in Fig. 8. The inter-station spacing in the optimum network works out to be of the order of 200-250 km for Peninsular India. The corresponding spacing in the geotectonically complex Himalayan region with high degree of lateral heterogeneities is relatively lower, being 100-150 km along the main longitudinal trend and about 50 km across it. This makes network density in the Himalayan region larger than that in the Peninsular shield. The optimum network covering the mainland and to some extent the island regions of Andaman-Nicobar and Lakshadweep, comprises 177 seismic stations in all. In this network, 93 new observatories will have to be established, while some of the existing stations among the remaining 84 stations need to be upgraded to advanced digital grade. Out of the 84 existing stations, 47 are currently operated by IMD and 37 belong to other institutions in the country, which need to be integrated in the national network. As regards source location, the hypocentral solutions of all the detected earthquakes within the outer boundary of the main network are expected to have an accuracy of $\pm$ 2 km in epicentre and within $\pm$ 5 km in focal depth. However, this precision cannot be maintained in respect of sources on the extreme margins of the country and indeed those situated off-shore, where the source location accuracy will degrade to 6-10 km in epicenter and about 20 km in focal depth.

4. Conclusions

(*i*) There is an urgent need not only to strengthen but also to standardize the existing seismological observatories in the country to maintain uniformity in observational practices, data formatting and analysis. The existing infrastructure, manpower and resources in the country could then be utilized optimally and effectively. This is also expected to provide a major thrust to seismological research in the country, as the seismic data will be available on a broader platform to the scientific community.

(*ii*) An optimum design for the Indian seismological network region has been configured on robust considerations with an objective of monitoring earthquakes of magnitude 3.0 and above occurring anywhere in the country.

(*iii*) A rational basis that relies on a two-pronged approach has been adopted in the construction of the optimum network. It incorporates a practical way of placing seismic stations considering salient seismotectonic features and providing uniformly good coverage incorporating results obtained from a theoretical simulation of an ideal network, both duly integrated with the seismic wave attenuation models deduced separately for the peninsular shield and the Himalayan regions.

(*iv*) The optimum network comprises 177 seismic stations in all with 93 new stations and 84 existing observatories, 47 of which are currently operated by IMD and the remaining 37 belong to all other institutions in the country.

(*v*) All the stations of the optimised network have to be equipped with identical state-of-the-art triaxial broadband digital seismic equipment with most modern communication facilities for near real time data access. The stations not meeting this advanced technology standards will have to be upgraded appropriately.

(*vi*) The study reveals that the inter-station spacing of 200-250 km in the peninsular shield region is adequate in view of the required detection and location capability of the net, while that in the geotectonically complex Himalayan region is relatively smaller, being 100-150 km along the main longitudinal trend and about 50 km across it.

(*vii*) Presupposing that the seismic wave travel-time model in the region of signal detection is accurately known, the proposed network ensures design goal of source location accuracy within 2 km in epicenter and within 5 km in focal depth in respect of all seismic events on the mainland enclosing the outer boundary of the network. For earthquakes on the extreme margins of the country and indeed those which may occur off-shore, the location inaccuracies are typically 6-10 km in epicenter and up to about 20 km in focal depth.

Acknowledgements

The authors are thankful to the Director General of Meteorology for permission to publish the paper. Most of the material in this paper is adopted from the two reports (IMD, 1999, 2000) on which the paper has firm basis. The assistance provided by Shri Sansar Singh, Assistant Meteorologist II of IMD in the preparation of the report on "Integration of Network of Seismological Observatories in India" is duly acknowledged.

References

Arora, S. K., Varghese, T. G. and Basu, T. K., 1978, "Relative performance of different triangular networks in locating regional seismic sources", Proc. Ind. Acad. Sci., *Earth Planet. Sci*, **87A**, 11, 271-281.

Arora, S. K., Basu, T. K. and Krishnan, C. A., 1980, "Relative performance of augmented seismic network under random arrival-time errors", Proc. Ind. Acad. Sci., *Earth Planet. Sci*., **89**, 3, 359-367.

Bhattacharya, S. N., Jain, P. S. and Srivastava, H. N., 1982, "Error estimation in hypocentral location using Beas project network data by Monte Carlo simulation", Proceeding of VIII Symposium of Earthquake Engineering, University of Roorkee.

Bhattacharya, S. N. and Dattatrayam, R. S., 2000, "Recent advances in seismic instrumentation and data interpretation in India", *Current Science*, **79**, 9, 1347-1358.

Five to ten years profile of seismological studies in India by a Committee of experts. Chairman : Dr. A. S. Arya. (1987).

Gupta, H. K., Skoko, D. and Sato, Y., 1973, "Accuracy of determination of epicentre and origin time of small earthquakes in the Indian sub-continent", Bulletin of Seismological Society of America, **63**, 1901-1912.

India Meteorological Department, 1986, Seismological Organization : Status report and recommendations by Shri. H. M. Chaudhury.

India Meteorological Department, 1999, An optimum seismological network in India, 1-48.

India Meteorological Department, 2000, Report of the committee for integration of network of seismological observatories in India, 1-105.

Lee, W. H. K. and Lahr, J. C., HYPO-71, 1975, "A computer program for determining hypocenter", US Geological Survey Open File-Rep., revised edition.

Report of Group on Seismology, 1971 Government of India, Planning Commission, New Delhi, Chairman: Dr. A. N. Tandon.