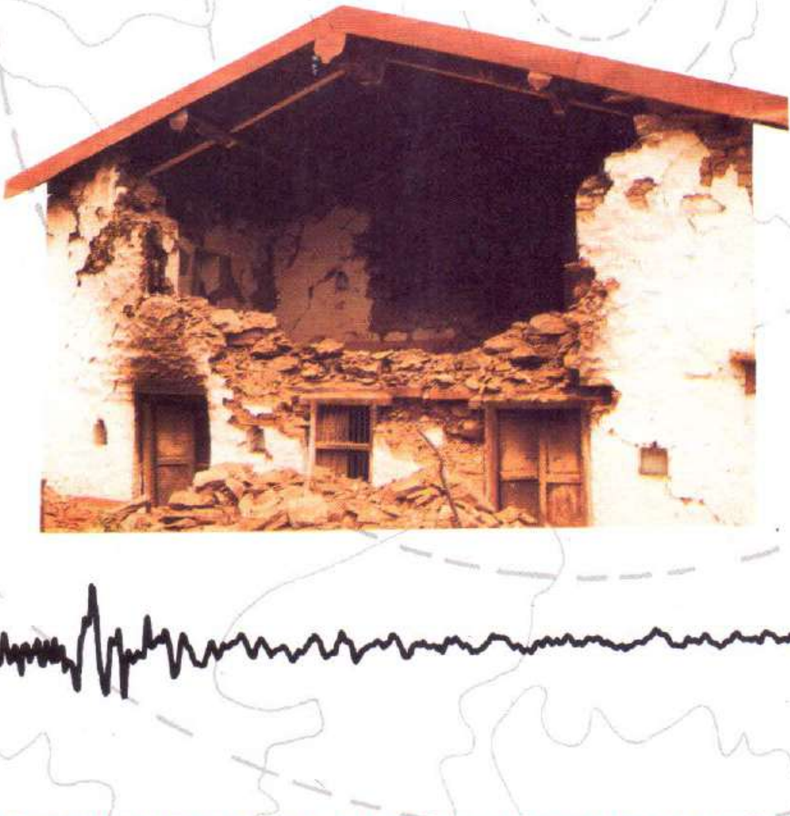
A REPORT ON

CHAMOLI EARTHQUAKE OF MARCH 29, 1999

CHAMOLI



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PREFACE

The Department of Earthquake Engineering is actively engaged in teaching, research and development of earthquake resistant design and construction practices. It also disseminates the knowledge in earthquake engineering by organizing short-term courses and symposia/conferences. It also provides consultancy services to various government and private organizations. The Department as one of its important activities has been conducting damage surveys and engineering assessment of civil engineering structures after disastrous earthquakes since its inception in 1960 as School of Research and Training in Earthquake Engineering, University of Roorkee. The objective of such surveys are (a) to assess the damage and to understand the deficiencies in construction (b) to advise the local administration for rehabilitation and reconstruction (c) to suggest methods of retrofitting and (d) earthquake safety planning for the future.

Another major activity of the Department is to acquire seismological data through deployment of instruments in the field. The Department has deployed networks for acquiring strong ground motion, micro earthquake and broad band data of earthquakes. The strong motion array in UP Himalayas has recorded the Chamoli earthquake of March 29, 1999 and very valuable data has been obtained. One of the broad band stations deployed at Narendranagar observatory has recorded the event closest to the epicenter.

The Department had sent a team to survey the damage caused by the Chamoli earthquake of March 29, 1999 in the Kumaon Himalayas. The team consisting of Dr. M.L. Sharma, Dr. D.C. Rai and Mr. R.N. Dubey surveyed the area during April 1999. The present document consists of the damage survey report of the earthquake by the team and its interpretation in terms of isoseismal map and performance of buildings and bridges. It also contains the seismological aspects, the data acquired, the causes of damage, construction quality, locally available material, remedial measures and a report on the scientific issues raised with the comments and suggestions on various reports published in media. The recommendations for further course of action as a result of lessons learnt from the damages in this earthquake are also presented. I hope this report will be of great use to engineers and scientists.

Compiling and bringing out this report in its present form by Dr. M.L. Sharma and Mr. R.N. Dubey is very much appreciated.

Place: Roorkee
Dated: June, 2000

D.K. Paul
Professor and Head

CHAMOLI EARTHQUAKE OF MARCH 29, 1999

A moderate earthquake measuring 6.8 on Richter Scale occurred in north-west UP on March 29, 1999 at 00.35 hrs. and shook north and north west part of Uttar Pradesh causing considerable damage to life and property in the region. The epicenter of the earthquake was close to Chamoli at latitude 30.429° N and longitude 79.228° E the maximum intensity observed was VIII on MSK scale. The fault plane solutions indicated thrust type of faulting for the event. The focal depth of the event has been estimated as 21 km from the data collected and the same was estimated by USGS also. The number of lives lost is put at 103 with several hundred others injured grievously.

The Garhwal Lesser Himalaya region where the earthquake occurred forms part of the plate boundary between the Indian and the Eurasian plates which are colliding and is characterised by three major northward dipping thrust zones separated by geological sub-provinces. The region is seismically very active and has attracted attention of researchers in the field of seismicity and earthquake engineering. Several Earthquakes of magnitude <4 have occurred in this region during the last three years. Also a magnitude 6.5 earthquake was experienced in this area with epicenter close to Uttarkashi in Oct. 1991 which caused considerable damage and killed nearly 1000 people. This was the first major shock after many years in this area which is often described by seismologists as gap area. A number of strong motion earthquake recording instruments have been installed under various schemes and projects in this area and good instrumental data have been obtained on these during and after the main shock of March 29, 1999. As many as 11 accelerographs and 16 structural response recorder stations established by the Department of Earthquake Engineering recorded the event and data was picked up, processed and analysed. The peak ground acceleration recorded was 0.35 g at Gopeshwar close to the epicenter. The Department also had a three component broad band seismograph deployed at Narendranagar seismological observatory which also recorded the main shock as well as the aftershock sequence. More than 100 aftershocks of magnitude greater than 2.0 were recorded within about one month of the event. Out of these 9 aftershocks with magnitude greater than 4.6 were recorded on the accelerograph at Gopeshwar.

The general practice of building construction in the region employs stones in mud mortar with slates roofs generally supported on timber or bamboo trusses. This form of construction attracts the fury of earthquake more than other forms of constructions like brick buildings with seismic strengthening measures or reinforced concrete buildings. However, even stone buildings can be strengthened to resist earthquake shocks expected in this region. Damage survey of the earthquake affected area has shown that more than 4500 houses were damaged in the two districts of Chamoli and Rudraprayag while other forms of construction have escaped with minor damages. This is indicative of the earthquake resistant nature of that type of construction. Economically well off people in the region have now started constructing houses in brick masonry even though the cost of transportation of bricks from the plains adds substantially to the total cost of the building. The performance of such structures during the recent earthquakes has demonstrated its usefulness much more than the stone masonry construction as employed by large number of economical weaker sections.

The earthquake has once again has brought out the necessity of implementing earthquake resistant measures which have been developed and put into the form of documents released through the Bureau of Indian Standards. It is, however, for the scientific community as well as other governmental and social organizations to educate the local inhabitants to adopt such earthquake protective measures for their dwellings as well as for themselves through extensive training and awareness programmes.

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Chapter 1

SEISMOLOGICAL ASPECTS

M. L. Sharma and R. N. Dubey

Introduction

An earthquake of magnitude 6.8 rocked Chamoli area of the Kumaon Garhwal Himalaya region at 00:35 on 29th March 1999. The earthquake was very widely felt in North India injuring about 400 people and took a toll of 103 human lives. A total of about 4500 houses in the Chamoli and Rudraprayag districts were severely damaged. The damage was confined mostly to the conventional type of construction in the region mainly of stone masonry with mud mortar. The earthquake occurred in Lesser Himalaya between Munsiari and North Almora Thrust. The epicenter of the earthquake is reported to be in the north east of Chamoli at 30.429° N and 79.228° E (USGS). The fault plane solutions with NP1: Strike=290°, Dip=14°, Slip=90°; and NP2: Strike=110°, Dip=76°, Slip=90° show it to be thrust type of faulting. This chapter deals with the seismological aspects of the Chamoli earthquake. Along with the description of geology of Kumaon Himalayas and tectonics of the region, this chapter describes the observations of the damage survey and the isoseismal map prepared based on the damage survey.

Kumaon Himalayas

The Kumaon Himalaya stretches from the Kali River, which defines the India-Nepal border in the east, to the Tons-Bhabhar valleys demarcating the eastern border of Himachal Pradesh. It comprises the districts of Pithoragarh, Almora, Nainital, Pauri, Chamoli, Uttarkashi, Tehri and Dehradun. The inner populated region is well connected with a network of asphalted roads and there are a number of fair-weather feeder roads constructed by the Forest Department, which lead to the remote forested interiors.

The Kumaon Himalaya falls into well defined physiographic belts, each being a distinct geological unit like the Bhabhar, the Siwalik, the Lesser Himalaya, the Great Himalaya, and the Tethys or Tibetan Himalaya (Valdiya, 1980).

The submontane Bhabhar is a piedmont belt in the foothills. The Outer Himalayan Siwalik Range, 900-1500m high, built up of Late Tertiary sedimentaries, exhibit a rugged and restive topography characterized by steep hill-slopes and deep valleys with crumbling walls scarred with landslides. This young mountain range seems to be tectonically active and is said to be still rising.

Separated from the Siwalik by the Krol Thrust (Main Boundary Fault) is the Lesser Himalaya 1500 to 2500m high. It has a comparatively mild and mature topography with gentle slopes and deeply dissected valleys, which suggest that the rivers and streams are still furiously at work The highest peaks of this central belt of the Precambrian-Palaeozoic sedimentaries and granite-injected metamorphics are Dudhatoli (3114m) east of Pauri and Nag Tibba (3022m) north of Mussoorie.

The northern belt of the Great Himalaya with its peaks soaring 6500 to 7200 meters high is characterized by precipitous scarps and vertical-walled gorgeous valleys and tumbling and foaming rivers. This belt of very youthful topography is tectonically still active and paradoxically is made up of the oldest rocks of the Himalaya - the Precambrian metamorphics and granitic gneisses.

To the north of the formidable Great Himalaya lies the vast expanse of what is known as the Tethys or Tibetan Himalaya made up of sedimentary rocks ranging in age from the late Precambrian to Cretaceous. This extremely rugged vegetationless and sparsely populated zone of the frigid climatic conditions evinces comparatively milder tectonic instability.

The Lesser Himalayan terrain is dominated by the imposing mountain rampart of the Nag Tibba Range that lies in a great sprawl from end to end immediately to the north of the Siwalik Range. This prominent physiographic feature consists in fact of two ranges, each disposed in the NW-SE direction. The southern range extending from Nainital (2591m) through Landsdowne (1837m) to Mussoorie (2510m) rises abruptly to great heights over the Siwalik ranges. The northern range extends through Kranteshwar (2196m) near Champawat, Devidhura, Ranikhet (1849m) Dudhatoli (3314m), Nag Tibba (3022m) to Jaunsar (1818m). West of the River Yamuna and east of the River Ladhiya these two ranges merge into one. To the east, the Nag Tibba Range extends into Nepal through Dandeldhura towards Hiunchuli massif, and to the west it extends into Himachal through Chandpur.

Geology and tectonics of the area

The Kumaon Himalaya is one of the most fascinating segments of the Himalayan arc, and in many ways quite unique in its geologic setting. Four major lithotectonic units, each characterized by distinct lithological composition, stratigraphic succession, structural pattern and magmatic history, have been recognized in the Kumaon Lesser Himalaya Valdiya (1980). These are (1) the autochthonous unit of the Damtha and Tejam groups of Precambrian sedimentaries exposed in the vast window in the inner (northern) belt of the Lesser Himalaya; (2) the Krol Nappe of the outer (southern) Lesser Himalaya constituted of the Jaunsar and Mussoorie groups of sediments of possibly Palaeozoic ages. In the inner Lesser Himalaya the Krol Nappe is considerably attenuated and is represented by Berinag Nappe made up of a lithostratigraphic unit which also forms a part of the Jaunsar group of the Karol Nappe; (3) the Ramgarh Nappe and its extensions that cover parts of the Berinag and Krol Nappes, consisting of a lithology that resembles the upper part of the Damtha group of the autochthonous zone; and (4) the Almora Nappe, its klippen and the root at the base of the Great Himalaya, made up of medium-grade metamorphics intruded by syntectonic and profoundly deformed granitic suite. The root of the Almora Nappe has been thrust over by a lithotectonic unit composed of rather high-grade metamorphics of Precambrian age. This lithotectonic unit of the Kumaon Himalaya belongs to the Great Himalayan realm. The other unit is formed of the Later Tertiary sediments of the

Siwalik in the Sub-Himalaya, which has been sharply severed from the Lesser Himalaya by Krol (Main Boundary) Thrust.

The vast window of the inner Lesser Himalaya reveals the autochthonous Precambrian sedimentary groups involved in complicated tight and cross foldings and exhibiting surprisingly little metamorphism, even though they occupy the lowermost levels in the stupendous succession of rock-formation. The Lower Riphean Damtha Group at the base consists of the Chakrata Formation of turbidite flysch, imperceptably grading upwards and laterally into the slates-quartzites assemblage of the Rautgara Formation. The Rautgara includes a vast proportion of intrusive dolerites and basalts. The Damtha is conformably succeeded by the Tejam Group, comprising the Deoban (Gangolighat) and Mandhali (Sor+Thalkedar) formations. The Deoban is made up predominately of dolomites characterized by prolifically developed branching stromatolites of the middle to lower Upper Riphean age. This formation imperceptably grades upwards into the pyritous-carbonaceous slates, marls and interbedded calcitic marbles of the Mandhali formation. Locally there are lenticular bands of intraformational conglomerates at the base of the succession. The carbonaceous slates have yielded palynofossils indicating an age anywhere between Vendian and Cambrian Valdiya (1980).

The Tejam Group has been thrust over in the inner Lesser Himalaya by a huge pile of quartzarenites and basic volcanics of the Berinag Formation, displaying apparent, generally conformable, relation with the underlying formation and tight to isoclinal overturned folding. Across the Tons River in the west, the Berinag joins up with what has been recognized as the Jaunsar just below the Chail Nappe on the Shimla Hills. The Berinag not only resembles in lithology with the Nagthat formation of the Krol Nappe to the south but is also observed to join up with the latter in southeastern Himachal. It is therefore suggested (Valdiya, 1980) that Berinag Nappe is a drastically attenuated- both base cut off and beheaded - northern extension of the Krol Nappe of the outer Lesser Himalaya.

In the outer Lesser Himalaya - the Nag Tibba belt - the Eocene-capped autochthonous Damtha in the north and the Siwalik in the south have been thrust over by 6000 meter thick succession of sedimentaries building up the huge Krol Nappe. The lithostratigraphic units involved in the Krol Nape are the impersistent Mandhali at the base, the Chandpur and Nagthat formations of the Jaunsar Group, forming the bulk of the tectonic unit, and the Mussoorie Group of Balloon, Krol and Tal formations constituting the top in the southern part only. At the base the Mandhali consists of black and green phyllites, plastically deformed marble and a variety of quartzites, including conspicuous conglomerate beds in the Jaunsar Hills. The Chandpur is metaflysch formation made up of olive-green and gray phyllite and metasiltstones. The Nagthat consists of quartzarenites (orthoquartzites) with subordinate slates, and includes synsedimentary basic volcanics and is the southern prolongation of the Berinag. The age of Jaunsar Group (Chandpur - Nagthat) is still a matter of speculation. It could be Lower Paleozoic although they also show lithological characters similar to those of the Lower Riphean (Precambrian) Damtha Group. But this could be purely coincidental. The Bilaini begins with a persistent horizon of conglomerate intercalated with greywackers and siltstones, which pass into carbonaceous slates and varicolored limestone. The succeeding Krol formation consists predominantly of carbonates: limestone marls and slates in the lower parts and dolomites in the upper.

The third Lithologic unit, lying below the Almora Nappe of the Crystalline rocks comprises the Ramgarh Group and its extension as imbricating sheets involved in the schuppen zone below the Munsiari Thrust. The fourth and the uppermost lithologic unit consist of a vast sheet of medium-grade metamorphics intruded by syntectonic granodiorite-granite suit occurring as sill like bodies of various dimensions. This is the Almora Nappe, which builds the upper part of the Nag Tibba range extending from Kali valley through Champawat and Ranikhet to Dudatholi in Pauri Garhwal. The root of the Almora Nappe is the Munsiari Formation constituting the base of the Great Himalayas.

The Lesser Himalaya is demarcated by two major thrust planes. In the south the young sedimentary Siwalik realm is severed from it by the Krol and Nahan Thrusts commonly called the Main Boundary thrust. In the north the Main Central Thrust (Vaikrita) delimits the northern boundary of the Lesser Himalaya against the Precambrian high-grade metamorphics of Great Himalaya. The Almora Thrust defines the tectonic base of the great Almora Nappe built up of medium grade metamorphics and granitoids. Constituting a major tectonic element of the structural framework of Kumaon, it is equivalent to the Jutogh thrust of Shimla Hills. The root lies at the base of the Great Himalayas, implying that it is the prolongation of the Munsiari thrust. Heim and Gansser (1939) have named the two flanks of this asymmetrically synformal thrust as north Almora thrust and South Almora Thrust, respectively.

The low angled boundary between the sedimentaries of the Berinag or Mandhali formation and crystallines of the Munsiari formation at the base of the Great Himalayas has been designated as Munsiari Thrust (Main Central Thrust). The low angle (15-30° N to NNE) Munsiari represents the root of the Almora Group forming the Nappe in the Lesser Himalaya, so that the Munsiari Thrust is the extension of the Almora Thrust. The Vaikrita Thrust is postulated as the plane that separates the epizonal succession of sericite-biotite schists, micacious quartzite, amphibolite and lenticular marble with granites and augen gneisses of the Munsiari Formation from the high-grade metamorphics of the Vaikrita group building the bulk of the Great Himalayas. The Vaikrita Thrust demarcates the northern boundary of the Lesser Himalaya. This thrust has moderate to low angle (30-45°) inclination due NNE in eastern and central and NE in western Kumaon and ENE to E in the Satluj valley in Himachal.

The high-grade crystallines and metamorphics of the Higher Himalayas are designated as Vaikiritas. Valdiya (1973, 1980) differentiated the central crystalline into three formations. The Vaikrita group consists of (1) Coarse grained Kyanite and locally sillimanite bearing garnet-muscovite - biotite schists (the Joshimath formation), (2) Garnetiferous biotite-rich massive quartzite interbedded with subordinate biotite-muscovite schist (the Pandukeshwar Formation) and (3) Phlogopite rich calc-silicate gneiss and marble intercalated with kyanite-sillimanite-garnet-mica schist (the Pindari Formation).

The lithotectonic unit encompassed in the earthquake affected area from south to north are Barinag quartzite and Deoban Carbonate of Lesser Himalaya, Metamorphics of Deoprayag Crystalline clippe and MCT zone. Deoprayag crystalline occurring as a thrust sheet over the Lesser Himalaya form a large synformal structure. The epicenter area lie within MCT zone and Lesser Himalaya zone. The geology and tectonics of the region is given in Fig. 1.

Seismicity of the region

Vast areas of India along the Himalaya and adjoining plains are susceptible to grave earthquake risk. The Himalaya tectonic zone, being a collision plate boundary, is manifested with a number of north - dipping thrusts that are exposed at the surface. According to Seeber et al., (1981) these thrusts originate at a decollement surface dipping 5° towards north at depths ranging from about 12 to 20km. Fault plane solutions of moderate sized earthquakes depict upthrusting from the north along shallow dipping planes (e.g. Ni and Barazangi, 1984). The seismicity belt is mostly confined in between MCT in the north and MBT in the south, though closer to MCT.

The Himalayan arc zone, a collision plate boundary, has most recently ruptured in the western sector (1905 Kangra earthquake), in the central sector (1934 Bihar - Nepal earthquake and 1988 Bihar earthquake), and in the eastern sector (Assam earthquake of 1897 and 1950) relieving the accumulated stresses in these sectors. More recently, a damaging earthquake of magnitude 6.6 (Uttarkashi earthquake) occurred in the Garhwal Himalaya region on Oct. 20, 1991. This earthquake caused widespread damage to poorly constructed buildings killing about 800 persons. The epicenter of the earthquake was determined as 30.75° N and 78.86° E and focal depth as 12km. The earthquake was felt at very far distances including Delhi and maximum ground acceleration of 0.3g was recorded at Bhatwari. The earthquake was followed by a large number of aftershocks and a maximum intensity of VIII+ was observed. The Chamoli earthquake also occurred on Main Central Thrust zone in the east of Uttarkashi. The motion is again thrust type with focal depth of about 20km. The following contains some details of the damage survey carried out for the Chamoli earthquake.

Field observations and intensity distribution

The damage survey was carried out with the objective to assess damage pattern in the earthquake-affected area, to assign intensities and to prepare isoseismal map of the region. The intensities were assigned based on XII point Comprehensive Intensity Scale (IS: 1893-1984) which provides better classification of structure Types (A, B and C) and quantification of damage (single, few many and most) with its classification (Grade 1 to 5) which is commonly observable. The intensity at a locality is assigned based on the visual observations and through interview of local populace. The survey team tried to visit the affected area as much as possible, but some inaccessible areas could not be visited and were assigned intensities based on the interviews of local populace. The interviews were held based on a questionnaire as well as other experiences of the people.

The extent of the affected area was identified based on available information from television coverage and published reports in newspapers. Detailed mapping of earthquake intensities was planned so as to cover at least three of the highest isoseismals. The team started from 200 km SW of the epicenter starting from lesser-damaged area to more damaged area (increasing intensity). The route taken was Roorkee - Narendranagar - Tehri - Ghansalli - Chirbatia - Tilwara - Rudraprayag. From Rudraprayag the team took the route through Karanprayag - Nandprayag - Chamoli-Gopeshwar - Ghingrana. More intense survey was carried out in the epicentral area. The area lying between Gopeshwar and Okhimath could not be covered because of roadblocks due to landslides. Another route taken was Chamoli - Pipalkoti - Joshimath. Similar routes to Adibadri, Narayanbagad and Gadigaon were taken from Chamoli. From Rudraprayag a route to Okhimath was taken through Tilwara - Augustyamuni -

Okhimath - Guptkashi. To map the area on SE of epicenter a route through Srinagar - Pauri - Kotdwar - Najibabad - Hardwar - Roorkee was taken (decreasing intensity). Only the important observations are discussed, since it is difficult to include large volume of the data through the survey.

Generally, the houses in the Garhwal Himalaya region are built in stone masonry with mud mortar (kutcha houses). In the interior villages where the transport of building material is very difficult the houses are built with roofs generally made in timber trusses with slate on top of it. This type of houses built in olden time with comparatively larger stone size (Structure Type A) suffered maximum damage. In areas with easy approach from main road, many houses are plastered in cement sand mortar. Some of the houses also have RCC roofs. In some areas people have used fine slates also as packing material in stone masonry which behaved comparatively better. Mixed type of construction were also observed at many places where the ground floor is in stone masonry (old construction) while the upper floor (recent construction) is in brick masonry. In some cases houses are made up of prefabricated concrete blocks with reinforced concrete roof (Type B structures). Some of the buildings (mostly on roadsides) are constructed in brick masonry with cement sand mortar. Many well-built reinforced concrete buildings, belonging to Type C structures mostly government buildings and hotels, are also present in the area.

Tract I: Roorkee-Narendranagar - Chamba - Tehri

Most of the people were awakened by the earthquake motion and many rushed outdoors in Roorkee where intensity V could be assigned. The earthquake was felt by most of the people in Narendranagar. While no damage was observed in RCC buildings, minor cracks of Grade 1 to 2 were observed in Type A structures and few buildings of Category B suffered Grade 1 damage. Intensity V has been assigned to this location.

The primary school at Bemar built in random rubble masonry in 1985 at a distance of about 20 km from Narendranagar suffered Grade 3 damage. Figure 2 shows the delamination of the walls of the school because of lack of bond stones. The boundary wall about 75 cm thick got separated from the middle as shown in Fig. 3. However, the Jalagam Prabandh Yojna building (Type B) located at about 50 meters away from the Bemar primary school suffered no damage. Type A structures in the village Jalal located at about 3km NW of Bemar suffered Grade 1 damage. Intensity VI- is assigned to this locality.

The earthquake was felt by most of the people indoors and also outdoors and a few persons lost their balance at Chamba. Creaking sound of rattling of windows and doors was also heard. Grade 1 damage in buildings of Type B and in many of Type A was observed in this area. A sound like that of a moving truck was reported to be heard at the time of earthquake. Most of the people experienced predominantly horizontal motion. Sauce bottles fell from the open shelf in one of the shops and similar reports of falling objects were also reported in Chamba. Cracks in the buildings with stone masonry in mud and cement mortar were seen in Badshahi Thol located at about 10 km from Chamba. More than 50% houses were damaged in Dharsal and rest of them looked on the verge of collapse. Many people heard a sound like that of gushing water in the river. People were very scared of the impending rainy season, which would be disastrous since almost all the houses had developed cracks. However, well-constructed buildings at Pantnagar University Campus at Ranichori located at about 3 km from Badshahi Thol suffered no damage. Intensity VI has been assigned to this area.

There was no damage observed to the Type B and C buildings in New Tehri Township. One of the residential blocks in the colony-developed cracks of Grade 2 to 3 due to earthquake, which was declared unsafe. This may be probably due to subsidence in one of the sides of the building. Another block in the same locality developed cracks of Grade 1 to 2. The wall in N-S direction observed relatively more damage. Minor cracks in the houses made up of random rubble masonry packed with slates (Type A) were observed in Old Tehri Town. Three of the four minarets of the clock tower built in lime-surkhi and brick in 1892 fell from the top (Fig. 4) in Old Tehri Town. Figure 5 shows the major cracks developed in the house of Municipal Executive Officer, which may be attributed to its location on a slope. Intensity VI has been assigned to these places.

Tract II: Tehri - Ghansalli - Chirbatia - Tilwara - Rudraprayag

Major cracks were developed in most of the Type A structures (random rubble masonry in mud mortar) in Gadollia at about 5 km from Old Tehri Town. The motion during this earthquake was more intense as compared to Uttarkashi earthquake of 1991 as reported by the local people from Gadollia. Both the types of motions, i.e., vertical as well as horizontal were experienced by most of the people. Photographs in Fig. 6 show one of the damaged houses among many in Gadollia village. Structures of Type A experienced Grade 2 damage for most of the houses. Many houses in the village Asena developed major cracks (Fig. 6). Most of the houses experienced Grade 2 damage in the village Pilkhi located at about 7 km from Ghansalli. The nearby villages namely Nail, Bansola, Banchini, Thapla, Dwari and Devlangi reported to have experienced Grade 2 damage in Category A and Grade 1 in Category B houses. The houses with brick masonry in mud mortar also developed minor cracks. The motion in vertical as well as horizontal direction was experienced in this area. The main direction of motion was reported to be NE-SW. The Rajkiya Inter College built in 1968 in Ghumatidhar about 2 km from Pilkhi towards Ghansalli suffered no damage except some minor cracks. Figure 7 shows the college building constructed with stone masonry in mud mortar with cement plaster and RCC slab on first floor and tin shed on the roof. However, the kutcha house (the peon's residence) located few meters away from the college was badly damaged. Some of the kutcha houses were reported to have completely damaged in nearby villages around Mualgaon located at about 24 km before Chirbatia. Most of the houses (Category A) developed cracks of Grade 1 to 2. Intensity VI has been assigned to these places.

The village Mehar situated on the road leading to Bhatwari and Chaura experienced almost total damage. Figure 8 shows the damaged houses of village Mehar. Two parallel cracks of about 10 to 12 meters apart and approximately half cm wide were developed in the ground for as long as 500 meters in this village (Fig. 9). These fissures were also reported on the top of the same hill at two places, which seems to be a slope failure case (local phenomenon). In the villages Bhatwari and Chaura almost all the stone masonry buildings were totally damaged (Category A damage of Grade 4 to 5) (Figs. 10 and 11). There was no Category B or C houses in these villages. All the people were very frightened. Two deaths were reported from the village Chaura. Mostly the damage was done to the walls in N20° to NS direction. Intensity VII- has been assigned to these places.

Most of the kutcha houses were damaged in Chirbatia, which is the highest point in this area (2287m). Ground fissures of about half cm wide were seen prominently in N20° to NS direction in the ground for about 30 meters (Fig. 12). Similar types of fissures were also reported from the nearby places on the same slope. Wide cracks were observed in most of the houses as shown in Fig. 13. Most of the houses of Category A experienced Grade 2 to 3 damage. Intensity VI+ is assigned to this place.

While moving from Chirbatia to Tilwara, four fissures of about 1 to 2 cm wide, 3 to 4m apart, running parallel to each other on the main road were seen at Indranagar, which is about 20km from Chirbatia (Fig. 14). One of the houses situated on the roadside was totally damaged due to fissures passing through it (Fig. 15). The fissures were also reported in the nearby villages. The same fissures were again seen after a distance of about 1km on the roadside. The fissures were on the same side of hillock and seem to be a slope failure case. The kutcha houses in the nearby villages were reported to be damaged in and around Rudraprayag town. As such no damage was observed in Rudraprayag township, which may be due to comparatively better construction in the area. Intensity VI+ is assigned to this place.

Tract III: Karanprayag – Nandprayag - Chamoli - Gopeshwar

The damage along the roadside in Karanprayag township was lesser due to comparatively better construction of buildings most of which were brick/ stone masonry using cement sand mortar with RCC slab on the top. Minor cracks developed in the brick masonry houses in the village Langasu. Intensity VI has been assigned to these places.

Most of the houses of Category A were having at least Grade 2 damage in the village Marougaon. A sound like that of low flying airplane was reported to be heard. Few persons were reported to be injured. More than 40% of the houses in village Pursadi at about 6km from Marougaon were badly damaged. The construction type was same, i.e., of stone masonry in mud mortar and some of them having wooden frames made of Cheed wood planks. Cracks were also developed in the houses, which were plastered in cement sand mortar. Two persons were reportedly injured in this village. The villages namely, Palethi, Baluda, Theli and Mead were reported to have more than 50% houses damaged during this earthquake. One death was reported in Palethi, which is about 3 km from Pursadi. North-South trending ground fissures of the order of 2 to 3 cm wide were also seen in Pursadi village. These fissures could be seen all through the slope at the same height on the same side of the ridge (Fig. 16). The same phenomenon could be seen at lower heights at about 100 meter down the slope for about 1km length. This may again be a local slope failure incident. The houses through which the fissures passed were completely damaged (Fig. 17). However, the primary school built in 1987 in stone masonry with cement plaster situated very near to the village Pursadi developed minor cracks. Damage of Grade 2 to 4 to the kutcha houses were reported from village Maithana 2km away towards Nandaprayag from Pursadi. Intensity VII is assigned to Pursadi and Maithana.

Most of the kutcha houses were totally damaged (Category A, Grade 4 to 5) in Chamoli which was the worst hit area by the earthquake, which got its name after it. The market along the main road side is in the Lower Chamoli while most of the government offices and residences are in Upper Chamoli at a distance of about one km up the hill. Most of the houses of Category B suffered Grade 2 to 3 damage in this area.

In Upper Chamoli, the Chamoli jail was totally damaged and six deaths were reported. The jail was constructed in 1902 using large size irregular stones with mud mortar having about 2 ft thick walls. Due to lack of 'through' stones the thick wall got separated and the heavy stones fell during severe ground shaking causing deaths and injuries to jail inmates (Fig. 18). Similar was the case of women prison, which is a part of the main jail. Intensity VIII is assigned to Chamoli.

The village Ghingrana, located about 5km from Gopeshwar, experienced total damage of Grade 4 to 5 to most of the houses of Category A (Fig. 19). NE-SW motion was reported during the earthquake and the walls in NW-SE direction experienced more damage in comparison to NE-SW walls. People were unable to differentiate the vertical and horizontal motion. Intensity VIII is assigned to Ghingrana.

Tract IV: Chamoli - Pipalkoti - Helang - Joshimath

In the village Birhi, located at about 6km from Chamoli, more than 70% of the kutcha houses (Category A) experienced Grade 3 to 4 damage (Fig. 20). The owner of the Tapovan guesthouse reported the sudden change in the behavior of her pet dog before half an hour of the occurrence of the earthquake. The dog was very unrestful and running as if wanted to hide itself somewhere. The houses in the interior of the village, situated on the bank of river Birhi at about half km from the main road, were totally damaged. Intensity VIII- is assigned to this place.

More than 80% of the kutcha houses in the village Gadigaon, located on river Birhi at a distance of about 5km from main road suffered Grade 3 to 4 damage. However, the steel bridge was intact. Comparatively more damage was reported from [illegible] which is located at about 5km from Gadigaon. Lot of landslides were seen on the way to Gadigaon. Gronthal village (at a distance of 5km from Gadigaon) and Nijmula (at about 13km further SE of the Gadigaon) also experienced similar type of damage. Intensity VII has been assigned to these places.

Two deaths were reported from Pipalkoti, which is about 10km from Chamoli. Most of the houses of Category A experienced Grade 3 to 4 damage in Pipalkoti. Minor damage of Grade 1 to 2 was observed in Category B and C type of houses. The houses in Pipalkoti where the ground floor was constructed in stone masonry (older) and the upper floor (recent) was constructed in brick masonry were damaged with major cracks in the lower portion, which in turn damaged the upper floor. One of the houses located on the bank of the river and very near to a temple was badly damaged (Fig. 21). Two deaths were reported from the same house. The people could not run because of the intensity of the motion was too high to walk. While the first shock was of smaller intensity injuring few people, the immediate second shock (main shock) caused enormous damage to most of the houses and deaths, as people could not come out of their houses. The houses built in brick masonry were also damaged. Intensity VIII is assigned to Pipalkoti.

Most of the kutcha houses experienced damage of the order of Grade 2 to 3 in Garudganga and Pakhi which is further north of Pipalkoti at about 10km distance. From Garudganga to Helang many landslides were triggered during the earthquake and could be seen on the roadside at various places. Most of the kutcha houses in the village Tangni experienced Grade 3 to 4 damage. Many such houses were reported to be damaged in the villages across the river Alaknanda namely Salena, Thena, Lihari, [illegible], Devgram, Pilkhi, Basena, Barki, Betha, Gera and Arosi. On the right bank of the river the villages namely Barosi, Dungri, Shaloor and Dungra experienced lesser damage in comparison to the villages on the left bank. Intensity VII has been assigned to these places.

The people were frightened from the earthquake and were sleeping outside their houses in the village Paini. Grade 1 to 2 damage to most of the kutcha houses was reported from this village. Two deaths were reported from village Gulabkoti where the damage was more in comparison to Paini. Two cows and two bullocks were also reported to be dead in this village. Most of the houses in this village experienced Grade 3 to 4 damage and major cracks were developed in almost all the houses. The primary school built in random rubble masonry with cement plaster on the walls in Gulabkoti suffered Grade 2 damage. Ground fissures upto 2 cm wide was developed on the roadside at about 2km before Joshimath, which may be a local phenomenon. Intensity VII- is assigned to these places.

Grade 1 damage in buildings of Type B and in many of Type A was observed in Joshimath. At a glance it appeared that lot of cracks were developed in almost all the houses here but after detailed inspection it was found that most the cracks were older and were developed due to subsidence. In the building of the SDM's office minor cracks were developed due to this earthquake, which were along the same lines of the older cracks developed due to subsidence on one side. Intensity VI is assigned to Joshimath.

Tract V: Karanprayag - Simli - Narayanbagad - Adibadri

Both types of motions, i.e., vertical and horizontal were experienced by the people in Simli located at about 6km from Karanprayag on the Karanprayag - Narayanbagad road on the bank of river Pindar. A sound like that of a passing truck was heard by most of the people. The houses built in random rubble with mud/cement mortar with RCC roof on both sides of river Pindar experienced Grade 1 to 2 damage showing the damage pattern parallel to the flow of river. Many landslides were seen parallel to the flow of river and some of the fissures developed due to them, were passing through some of the houses which experienced comparatively more damage. Many of the buildings built in brick masonry with cement mortar developed minor cracks very near to the lintel band. Intensity VI- is assigned to this place.

Major cracks in the walls were developed in random rubble construction while brick masonry construction experienced minor cracks in the walls in Narayanbagad. Most of the houses of Category A suffered Grade 2 to 3 damage and few Category B houses experienced Grade 1 damage. The villages namely Chulla, Bhagoli, Naili, and Nalgaon etc. falling on the way to Narayanbagad suffered Grade 1 to 2 damage in most of the kutcha houses. But the damage was lesser in comparison to what was seen on the way from Chamoli to Karanprayag. Major cracks were reported to have developed in the kutcha houses in villages near Adibadri located on the Karanprayag-Ranikhet road. The temple at Adibadri suffered no damage. Few of the houses of Category B developed Grade 1 damage while most of the Category A houses developed Grade 2 to 3 damage. Intensity VI- is assigned to these places.

Tract VI: Rudraprayag - Tilwara - Augustyamuni - Okhimath - Guptkashi

Houses of Category A developed Grade 2 to 3 damage while that of Category B developed minor cracks only (Grade 1) in Silli village situated on the Rudraprayag - Okhimath road very near to Augustyamuni. Intensity VI is assigned to this place.

Bhatwari Sonar village is located on the Tilwara - Okhimath route. Most of the houses built stone masonry in mud mortar (some of them also used cement plaster) were totally damaged (Grade 4 to 5). Again the walls facing NS were severely damaged. The village is placed in the epicentral tract. The inhabitants could not differentiate between the horizontal and vertical motion. Figures 22 and 23 show the damage to the buildings in this village. Intensity VII+ is assigned to this place.

The old temple of Lord Kedarnath developed cracks in the walls in Okhimath. The temple is built in stone masonry with mud mortar having very good wooden supports. Lot of the wooden work is used in frames supporting the whole building, doors, windows, and the balconies etc. As such no damage was done to the temple but other supporting buildings developed cracks of Grade 1 to 2. Intensity VI is assigned to Okhimath. Guptkashi observed lesser damage in comparison to Okhimath and intensity V+ is assigned to Guptkashi.

Isoseismal map

The damage survey was done in a region of about 200km by 200km extending up to Roorkee in the SW, Chamba in the west, Guptkashi in the NW, Joshimath in the NE and Narayanbagad in the south. Extensive survey was carried out in the meizoseismal area. Based on the observations and the intensities assigned to various places, isoseismals were drawn (Fig. 24). The places like Bemar, Bhatwari Chaura and Bhatwari Sonar lying westward of the epicenter in a line showed comparatively more damage. Likewise on the other side of the epicenter the places like Ghingrana and Pipalkoti also showed the same trend which shows focussing of the energy predominantly in EW direction. The same trend can be seen while looking at the damaged walls most of which are facing NS direction (shear wall). On the other hand in NS direction the intensity is decreasing at a much higher rate. It may be mentioned that little information could be obtained from the mountainous terrain of the Himalayas so as to constrain tightly the northern extent of the rupture. There is no road after Badrinath on the NE side of the epicenter.

The damage pattern in the epicentral region indicates that the rupture might have extended up to Bhatwari Sonar in the west and upto Pipalkoti in the east from where the damage decreased rather sharply. The southern edge of the rupture may be marked between Pursadi and Maithana where damage was similar to that at Pipalkoti. The northern edge of the rupture could be somewhere near the Mewana village. Somewhat higher intensities at Bhatwari, Chaura, Bemar and in some of the villages near Badshahi Thol may be a consequence of focussing of energy from epicentral area towards east and may not reflect close proximity with the rupture zone activated by the earthquake.

Discussions

The Chamoli earthquake was felt widely over North India. The death toll was reported to be 103 with around 400 injured during the earthquake. About 4500 houses, mostly stone masonry with mud mortar were totally damaged and about 25000 houses suffered damage of different grades in the Chamoli and Rudraprayag districts of Garhwal Himalaya. The isoseismal map shown in Fig. 24 reveals that the isoseismals were elliptical with major axis elongated in east west direction. The area covered under the intensity VIII, VII and VI was 2068 square km, 5852 square km and 24372 square km respectively. The elongation of isoseismals in EW directions shows the nodal plane

NP1 i.e., Strike=290°, Dip=14°, Slip=90° to be the main plane and NP2 as auxiliary plane. The entire Himalayan region of India and adjoining plains are susceptible to grave earthquake risk and the damage to the conventional construction in this area reveals that there is a necessity to educate local populace about earthquake resistant construction in the rural areas at the level of end users and local masons.

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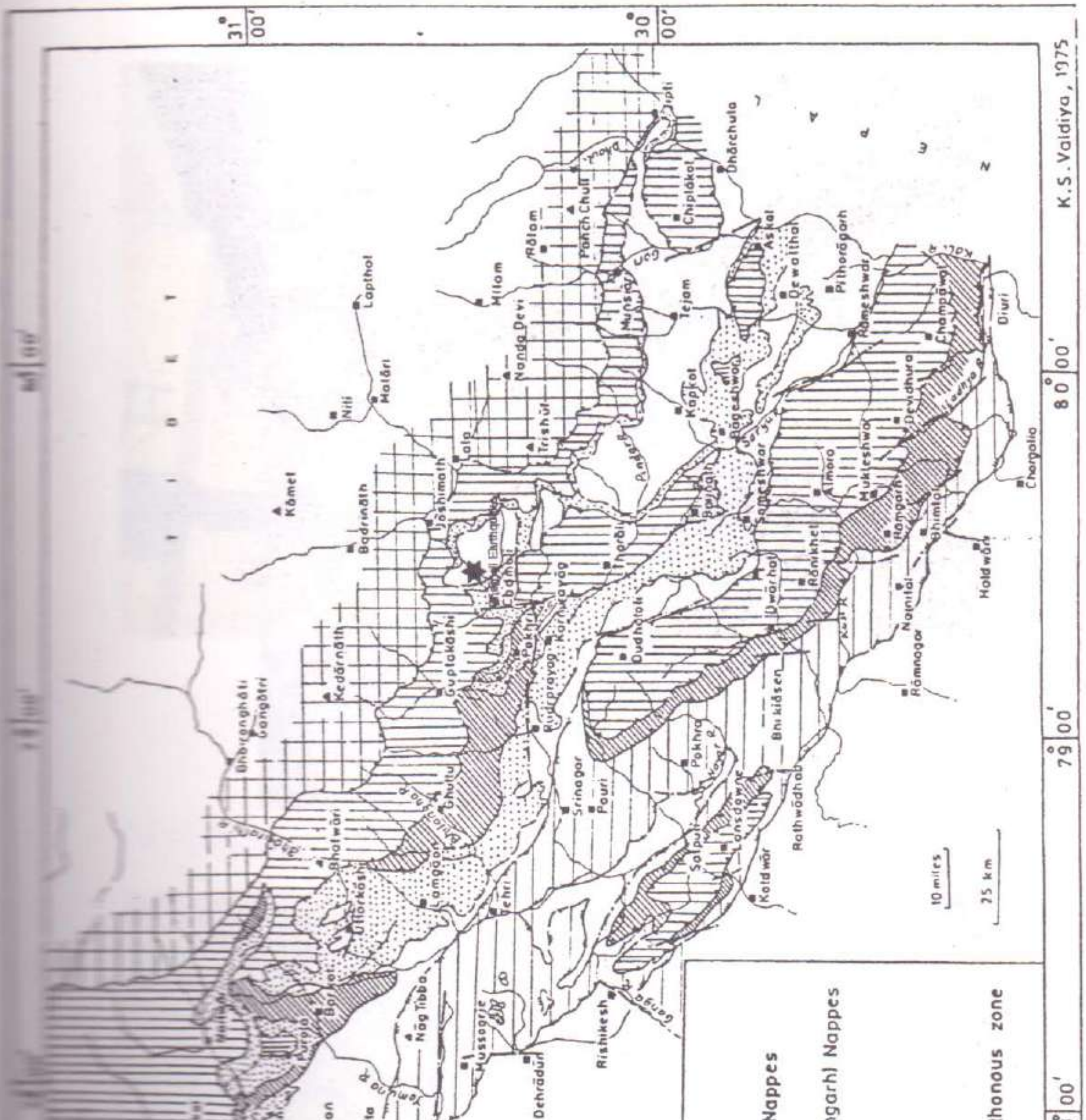

FIG. 1 GEOLOGY AND TECTONICS OF THE REGION. THE EPICENTER OF CHAMOLI EARTHQUAKE IS SHOWN BY (✱)

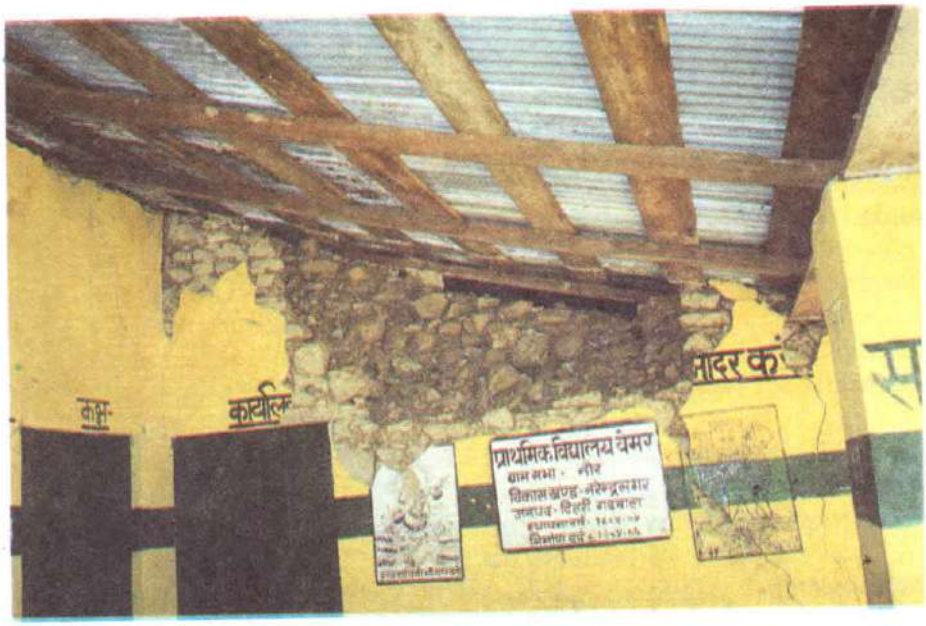

Fig. 2 Damaged primary school at Bemar

Fig. 3 Separation of baundary wall of primary school at Bemar

Fig. 4 Clock tower at Old Tehri Town

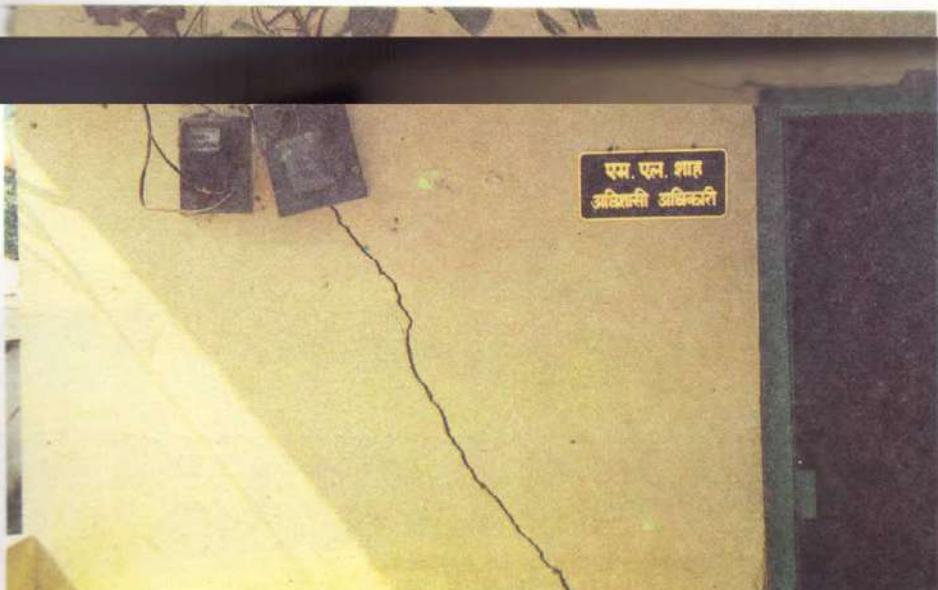

Fig. 5 Damaged house in Old Tehri Town

Fig. 6 Damaged house at Asena

Fig. 7 Rajkiya Inter college, Gumetidhar

Fig. 8 Damaged house at Mehar

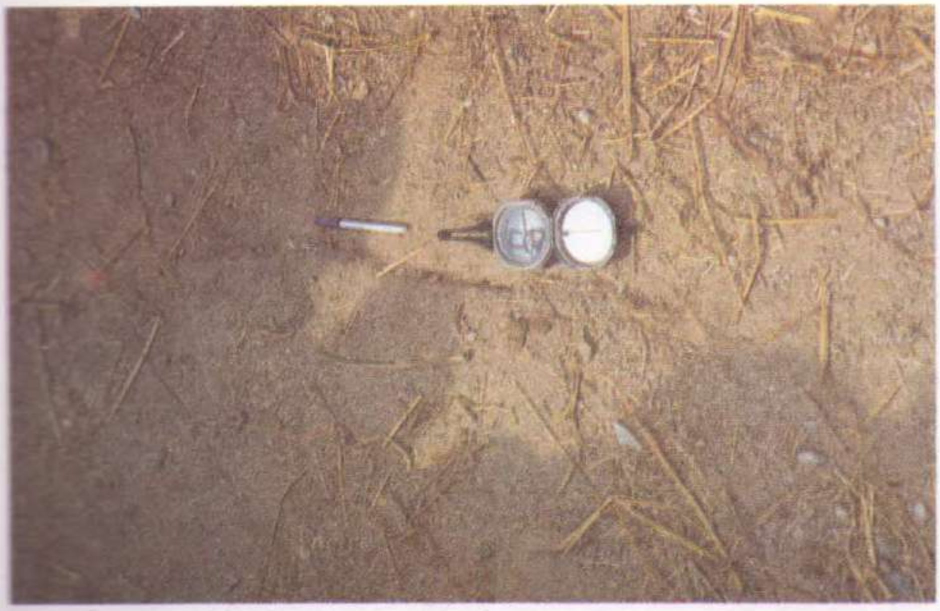

Fig. 9 Ground fissures at Mehar

Fig. 10 Damaged house at Bhatwari Chaura

Fig. 11 Damaged house at Bhatwari Chaura

Fig. 12 Ground fissures at Chirbatia

Fig.13 Damaged house at Chirbatia

Fig. 14 Ground fissures at Indranagar

Fig. 15 Damaged house at Indranagar

Fig. 16 Ground fissures at Pursadi

Fig. 17 Damaged house at Pursadi

Fig. 18 Damaged jail in upper Chamoli

Fig. 19 Damaged house in Ghingrana

Fig. 20 Damaged house in Birhi

Fig. 21 Damaged house in Pipalkoti

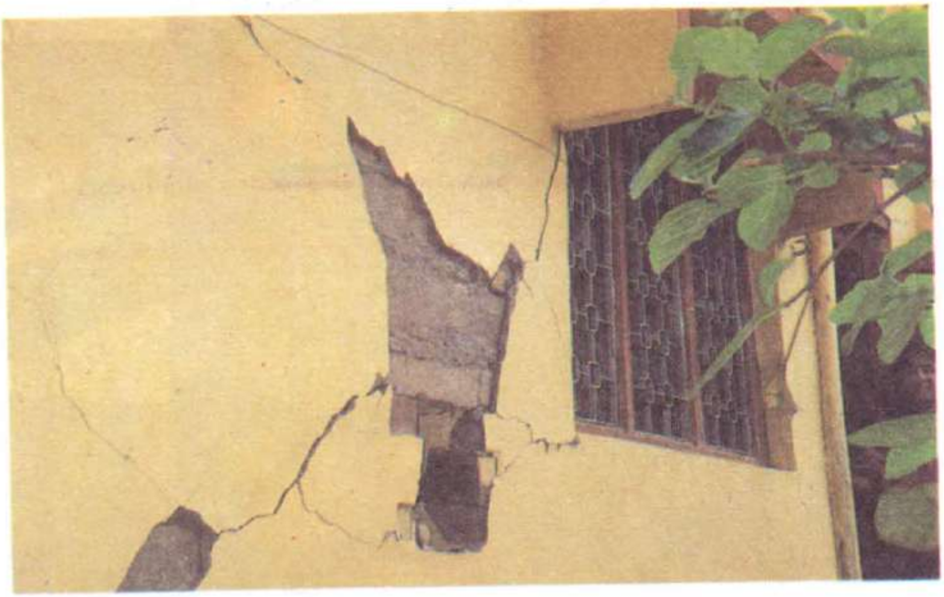

Fig. 22 Damaged house in Bhatwari Sonar

Fig. 23 Damaged house in Bhatwari Sonar

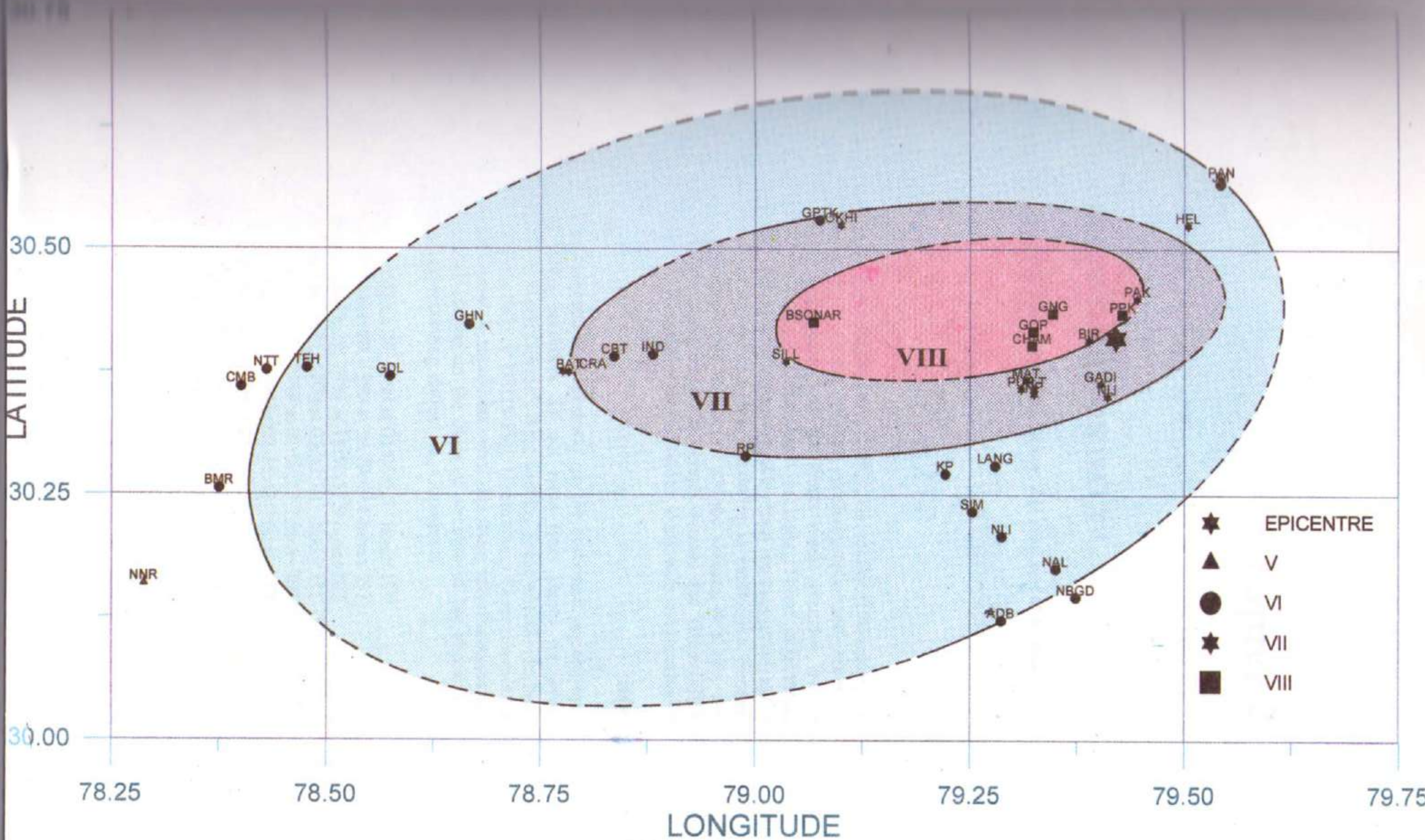

FIG. 24 ISOSEISMAL MAP OF CHAMOLI EARTHQUAKE

Chapter 2

STRONG MOTION DATA

M. Shrikhande, S. Basu, Brijesh Chandra, Ashok Kumar, J.D. Das, and M.K. Bansal

Introduction

The Department of Earthquake Engineering (DEQ), University of Roorkee, has installed and operates a network of strong motion accelerographs and structural response recorders (SRR's) in this region with the funds made available by the Department of Science and Technology, Government of India. These instruments record the ground accelerations during a strong earthquake which are then processed to investigate the nature of the forces exerted on a structure during an earthquake. Further, these records are also used to estimate the severity of ground shaking at a site. The Chamoli earthquake was recorded at eleven accelerograph stations and sixteen SRR stations. Figures 1 and 2 show the location of these stations along with the location of the epicenter.

Aftershock Sequence

Nine aftershocks were recorded at Gopeshwar (in the epicentral region) upto May 08, 1999. Since the SMA recorders do not have time stamp for event identification, it is not possible to exactly identify these shocks. These aftershocks have been tentatively identified with the help of USGS PDE (Preliminary Determination of Epicenters) Bulletins as given below. It should be noted that these identifications are only approximate and have been chosen on the basis of strength of the shock and proximity of the epicenter with the recording station, i.e., Gopeshwar

1. 5.4 M_b on March 29, 1999 at 01:06:5.5 hours IST
2. 4.7 M_b on March 29, 1999 at 14:19:49.1 hours IST
3. 4.6 M_b on March 29, 1999 at 18:50:57.9 hours IST
4. 5.3 M_b on March 31, 1999 at 02:32:10 hours IST
5. 5.1 M_b on April 07, 1999 at 01:07:23.7 hours IST
6. 4.6 M_b on April 07, 1999 at 02:16:40 hours IST
7. 4.9 M_b on April 07, 1999 at 21:19:12.7 hours IST
8. 4.9 M_b on April 14, 1999 at 22:54:27.8 hours IST
9. 4.5 M_b on May 07, 1999 at 22:42:01.8 hours IST

Ground Motion Parameters

Various parameters have been defined to characterize severity of strong shaking. The peak ground acceleration (PGA) is most widely used parameter to measure severity of earthquake. However, the PGA is a rather poor parameter for measuring severity of strong motion due to various reasons such as, its possible association with a pulse of very high frequency, irregular local topography, interaction of large structure at the site of recording etc.

Arias (1970) defined earthquake intensity as sum of total energy per unit weight stored in undamped oscillators uniformly distributed with respect to their frequencies at the end of the earthquake:

$$I_A = \frac{\pi}{2g} \int_0^{T_D} [\ddot{x}(t)]^2 dt \qquad (1)$$

where $\ddot{x}(t)$ refers to the ground acceleration, g is acceleration due to gravity and T_D represents the earthquake duration. Thus duration and amplitude is implicitly considered in the definition of I_A. Since $\ddot{x}(t) = 0$ for $t > T_D$, the equation (1) can also be written as

$$I_A = \frac{\pi}{2g} \int_0^{\infty} [\ddot{x}(t)]^2 dt = \frac{1}{2g} \int_0^{\infty} |X(\omega)|^2 d\omega \qquad (2)$$

where $|\mathbf{X}(\omega)|$ is the Fourier amplitude spectrum of $\ddot{x}(t)$. Thus I_A will be large for strong motion with significant amount of high frequency components, high amplitude and long duration.

Housner (1975) uses the mean square acceleration during the rise time of strong motion to define earthquake average power. Let

$$I = \int_0^{T_D} [\ddot{x}(t)]^2 dt \qquad (3)$$

be the total energy in a strong motion. The earthquake average power is defined as

$$P_a = \frac{1}{Ts} \int_{t_{0.05}}^{t_{0.95}} [\ddot{x}(t)]^2 dt \qquad (4)$$

where $t_{0.05}$ and $t_{0.95}$ are the time t at which I has 5% and 95% value respectively and the rise time is defined as $T_S = t_{0.95} - t_{0.05}$. Trifunac and Brady (1975) defined T_S as the duration of strong motion part of an accelerogram. The root mean square of P_a is the measure of average rate of input energy to an elastic system and is denoted as $rms_a = \sqrt{P_a}$. The larger value of P_a is obtained for an accelerogram which is of short duration and impulsive in nature. The value of earthquake power and Arias intensity is comparable. Both I_A and P_a are fairly good indicator of damage potential for brittle structure.

The elastic response spectra indicate directly how a linear elastic single degree of freedom (SDOF) system responds to strong ground motion. It also indicates maximum elastic deformation produced in structures having periods in the range of computation. However, it cannot be a good predictor of damage potential as the damage is primarily an inelastic phenomenon. For ductile structure the damage depends on duration of strong motion, number of stress reversals and amplitude of vibration excursions. Number of stress reversal and inelastic deformation are largely dependent on strong motion duration. To measure intensity of ground shaking from the elastic response of structure Housner (1952) proposed an average response in a range of periods. This measure is defined as spectral intensity and is given by

$$SI(\zeta) = \int_{0.1}^{2.5} S_v(\zeta,T)\ dT \tag{5}$$

where T is the period of SDOF, and $S_v(\zeta, T)$ represents the relative velocity spectrum. Although originally it was proposed for damping ratio of $\zeta = 0.02$, but presently it is customary to calculate SI(0.05). In the range of period Tε [0.1,2.5] and for lightly damped structure $S_v(\zeta, \omega_0) \approx S_{pv}(\zeta, \omega_0)$ and the equation (5) reduces to

$$SI(\zeta) \approx \int_{0.1}^{2.5} S_{pv}(\zeta,T)\ dT = \frac{1}{2\pi}\int_{0.1}^{2.5} S_{pa}(\zeta,T)\,T\,dT \tag{6}$$

Here, S_{pv} and S_{pa} respectively refer to the pseudo-velocity and pseudo-acceleration spectra. The equation (6) implies that spectral intensity is higher for strong motion with richer content of long period waveforms. The limitation of *SI* as a measure of damage potential parameter of earthquake is inherited from the definition of response spectra. The effect of duration of strong motion is not accounted for in response spectra. Thus spectral intensity *SI* value of approximately similar duration of strong motion records need to be compared for any meaningful conclusion.

Since a high value of PGA in a record could be because of a stray pulse of large amplitude, it is not a reliable parameter to measure the severity of ground motion. An alternative parameter Effective Peak Acceleration (EPA) has been defined by Watabe and Tohdo (1979). The EPA is defined as the peak value of amplitude truncated ground acceleration time history for which the spectrum intensity is 90% of that for the original time history. This way the effect of any spurious peak in the recorded time history is eliminated.

Araya and Saragoni (1984) simultaneously accounted for the effect of maximum amplitude, duration and frequency content of strong motion in prescribing earthquake destructive potential factor as

$$P_D = \frac{I_A}{\mu_0^{\,2}} \tag{7}$$

where I_A is Arias intensity and μ_0 is the intensity of zero crossing defined as N_0/T_D. N_0 is the total number of zero crossing in an accelerogram in total duration T_D with positive and negative slope. Among all the damage potential parameters proposed the equation (7) is most rational for linear elastic structure. However, it does not consider effect of inelastic deformations which is primarily responsible for damage.

In the following, Fig. 3 shows the interpolated contours for the largest recorded PGA during the main event in the region. Further, Table 1 summarises the results of analysis of strong motion data from the main event recorded at eleven stations in the UP Hills.

In addition to these main shocks nine aftershocks have been recorded at Gopeshwar (in the epicentral region). The Table 2 summarises the computed parameters for these nine aftershocks recorded at Gopeshwar.

The corrected time histories, response and Fourier spectra of the ground accelerations and recorded at Gopeshwar (for the main shock) and the SRR records at Gopeshwar are shown in Figs. 4-11.

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Table 1 Strong Motion Parameters

Site	Comp.	PGA (g)	EPA (g)	T_S (s)	I_A (10^{-2} g.s)	P_D (10^{-3} g.s^3)	P_a (10^{-1} g^2)	SI (ζ =0.05) (10^{-1} g.s^2)	f_c (Hz)
DEQ Roorkee	N 55 W (L)	0.056	0.017	27.235	0.449	0.191	0.945	0.242	2.42
Lat: 29.86 N	N 35 E (T)	0.047	0.015	28.620	0.333	0.127	0.667	0.160	2.56
Long: 77.89 E	Vertical	0.017	0.006	30.215	0.073	0.007	0.139	0.081	5.23
Tehri	N 63 W (L)	0.054	0.035	9.100	0.448	0.065	2.838	0.135	4.15
Lat: 30.37 N	N 27 E (T)	0.062	0.031	9.960	0.429	0.723	2.499	0.161	3.85
Long: 78.50 E	Vertical	0.034	0.015	11.580	0.132	0.009	0.656	0.090	6.02
Gopeshwar	N 70 W (L)	0.199	0.117	14.200	2.952	1.322	11.947	0.838	2.36
Lat: 30.40 N	N 20 E (T)	0.359	0.291	8.920	8.151	2.645	52.438	1.356	2.77
Long: 79.33 E	Vertical	0.156	0.049	7.240	2.548	1.603	20.230	0.328	6.30
Ukhimath	N 15 E (L)	0.091	0.039	16.280	0.824	0.061	2.930	0.234	5.79
Lat:30.50 N	N 75 W (T)	0.096	0.046	18.080	0.837	0.415	2.676	0.255	7.10
Long: 79.10 E	Vertical	0.047	0.025	15.040	0.198	0.099	0.765	0.146	7.06
Joshimath	N 80 E (L)	0.071	0.020	11.220	0.339	0.444	1.740	0.147	4.37
Lat:30.55 N	N 10 W (T)	0.063	0.035	13.700	0.592	0.675	2.483	0.357	4.68
Long: 79.57 E	Vertical	0.041	0.009	14.180	0.186	0.013	0.753	0.111	5.91
Chinyalisaur	N 43 E (L)	0.052	0.030	10.060	0.365	0.062	2.081	0.087	3.84
Lat:30.55 N	N 47 W (T)	0.045	0.025	10.560	0.476	0.065	2.601	0.108	4.29
Long: 78.33 E	Vertical	0.049	0.020	11.200	0.369	0.036	1.908	0.079	5.06
Ghansiali	N 00 E (L)	0.073	0.031	12.480	1.124	0.094	5.168	0.133	5.45
Lat:30.42 N	N 90 E (T)	0.083	0.049	12.400	1.450	0.111	6.702	0.142	5.71
Long: 78.65 E	Vertical	0.039	0.016	16.640	0.330	0.014	1.139	0.058	7.59
Uttarkashi	N 72 E (L)	0.054	0.033	11.200	0.318	0.023	1.630	0.153	5.83
Lat:30.73 N	N 18 W (T)	0.064	0.034	10.240	0.499	0.032	2.800	0.131	6.23
Long: 78.45 E	Vertical	0.023	0.009	13.140	0.073	0.016	0.318	0.092	3.39
Barkot	N 10 E (L)	0.017	0.006	11.940	0.025	0.002	0.123	0.020	6.21
Lat:30.80 N	N 80 W (T)	0.023	0.015	10.100	0.052	0.003	0.296	0.033	6.22
Long: 78.21 E	Vertical	0.019	0.009	11.420	0.028	0.001	0.144	0.018	7.69
Almora	N 53 W (L)	0.027	0.013	8.020	0.117	0.016	0.836	0.081	4.21
Lat:29.58 N	N 37 E (T)	0.028	0.019	7.780	0.085	0.011	0.631	0.060	4.32
Long: 79.65 E	Vertical	0.027	0.018	7.500	0.088	0.007	0.674	0.039	5.43
Lansdowne	N 70 E (L)	0.005	0.002	6.420	0.003	0.141×10^{-3}	0.023	0.006	6.69
Lat: 29.83 N	N 20 W (T)	0.006	0.002	6.780	0.004	0.131×10^{-3}	0.032	0.007	8.49
Long: 78.70 E	Vertical	0.011	0.003	6.420	0.007	0.295×10^{-3}	0.064	0.008	7.75

PGA - Peak ground acceleration, EPA - Effective peak acceleration, T_S - Duration of strong motion, I_A - Arias' Intensity, P_D - Destructiveness potential, P_a - Average power, SI - Spectrum intensity, f_c - Characteristic frequency.

Table 2 Parameters for Aftershocks recorded at Gopeshwar (30.40 N, 79.33 E)

Event	Comp.	PGA (g)	EPA (g)	T_S (s)	I_A (10^{-2} g.s)	P_D (10^{-3} g.s^3)	P_a (10^{-4} g^2)	$SI(\zeta=0.05)$ (10^{-1} g.s^2)	f_c (Hz)
Aftershock 1	Long.	0.041	0.028	8.800	0.104	0.016	0.683	0.078	4.08
	Tran.	0.065	0.040	5.080	0.198	0.027	2.257	0.070	4.31
	Vert.	0.046	0.029	4.700	0.152	0.006	1.879	0.028	8.17
Aftershock 2	Long.	0.011	0.007	7.420	0.015	0.003	0.116	0.022	3.76
	Tran.	0.011	0.005	8.500	0.013	0.002	0.094	0.015	4.41
	Vert.	0.022	0.004	4.880	0.017	0.669×10^{-3}	0.192	0.010	7.89
Aftershock 3	Long.	0.053	0.035	6.460	0.168	0.059	1.498	0.136	2.68
	Tran.	0.073	0.043	4.740	0.216	0.044	2.629	0.082	3.49
	Vert.	0.039	0.009	4.660	0.094	0.004	1.184	0.036	7.48
Aftershock 4	Long.	0.034	0.015	6.760	0.061	0.012	0.514	0.045	3.58
	Tran.	0.049	0.039	6.180	0.084	0.014	0.782	0.043	3.91
	Vert.	0.021	0.010	5.000	0.030	0.001	0.349	0.013	7.75
Aftershock 5	Long.	0.020	0.006	7.040	0.031	0.008	0.257	0.029	3.23
	Tran.	0.051	0.034	2.200	0.078	0.015	2.053	0.052	3.56
	Vert.	0.022	0.010	4.460	0.017	0.724×10^{-3}	0.227	0.013	7.76
Aftershock 6	Long.	0.039	0.019	5.380	0.061	0.014	0.655	0.047	3.33
	Tran.	0.046	0.010	3.100	0.079	0.012	1.464	0.055	4.11
	Vert.	0.036	0.026	4.020	0.045	0.002	0.647	0.019	7.68
Aftershock 7	Long.	0.036	0.023	5.660	0.047	0.009	0.481	0.040	3.52
	Tran.	0.058	0.049	2.480	0.099	0.013	2.308	0.048	4.36
	Vert.	0.018	0.007	4.320	0.029	0.001	0.391	0.014	7.91
Aftershock 8	Long.	0.053	0.035	5.780	0.212	0.069	2.109	0.095	2.78
	Tran.	0.083	0.030	4.420	0.299	0.084	3.929	0.125	2.98
	Vert.	0.033	0.017	3.780	0.059	0.004	0.905	0.036	5.88
Aftershock 9	Long.	0.025	0.015	6.220	0.039	0.009	0.360	0.037	3.24
	Tran.	0.036	0.021	4.720	0.047	0.006	0.573	0.039	4.23
	Vert.	0.019	0.017	6.160	0.020	0.001	0.188	0.014	7.00

PGA - Peak ground acceleration, EPA - Effective peak acceleration, T_S - Duration of strong motion, I_A - Arias' Intensity, P_D - Destructiveness potential, P_a - Average power, SI - Spectrum intensity, f_c - Characteristic frequency.

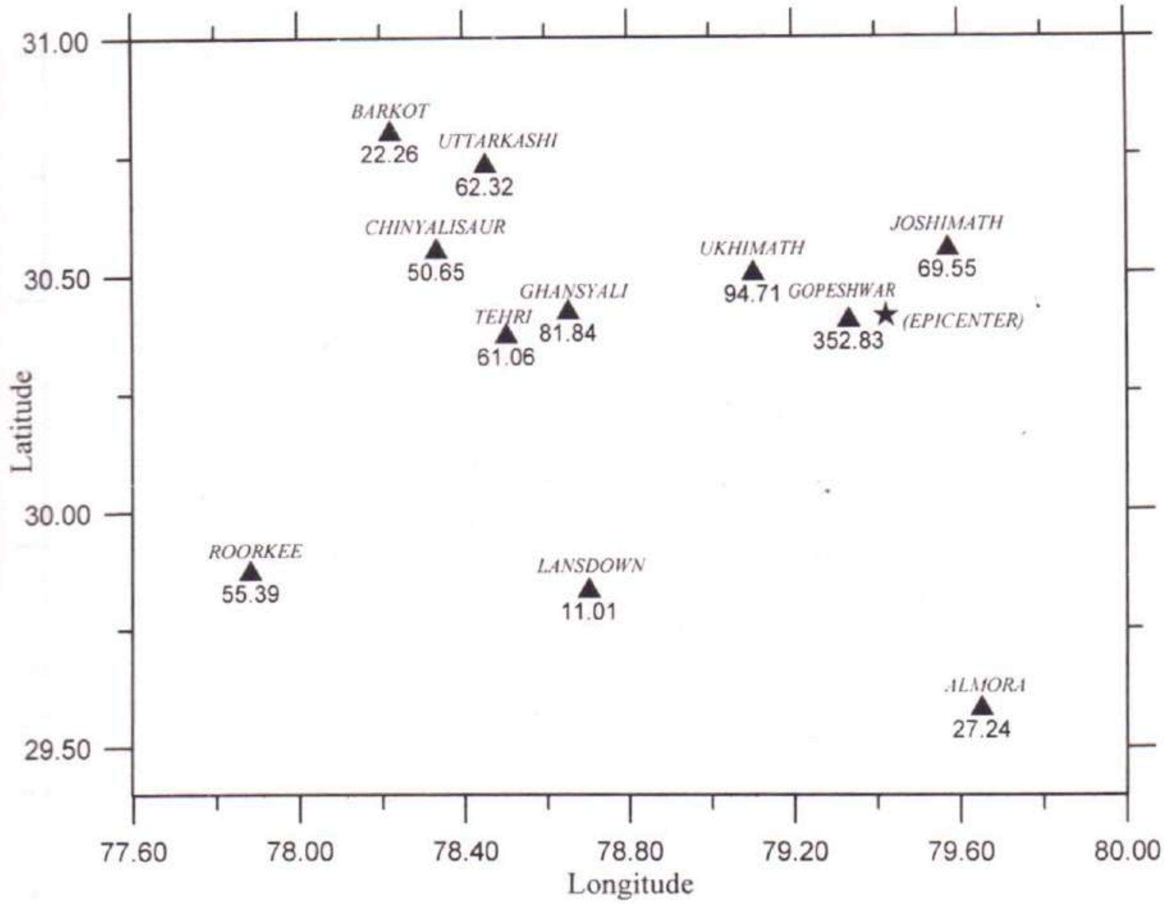


Fig. 1 Accelerograph stations that recorded Chamoli earthquake of March 29, 1999. Observed maximum horizontal acceleration (in cm/s*s) and epicenter.

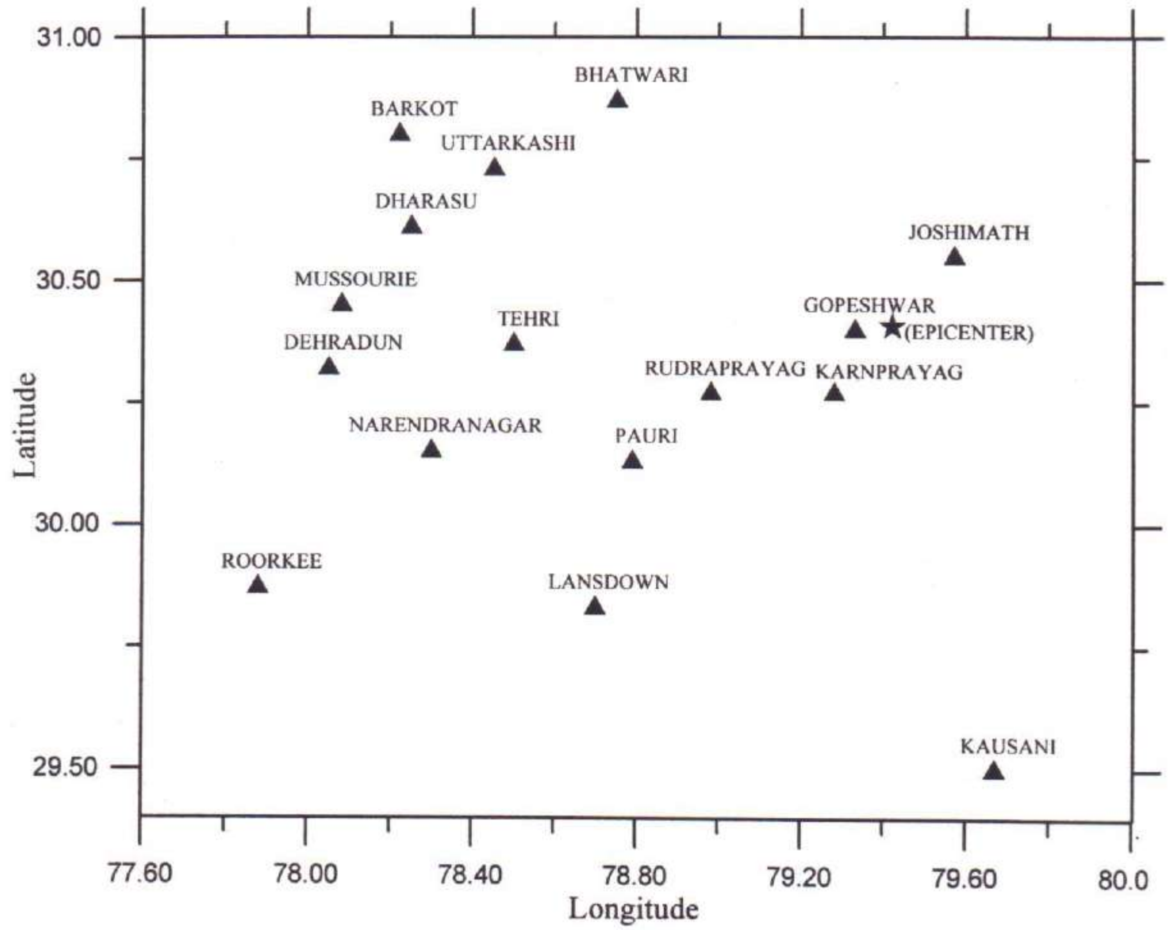


Fig. 2 SRR stations that recorded Chamoli earthquake of March 29, 1999.

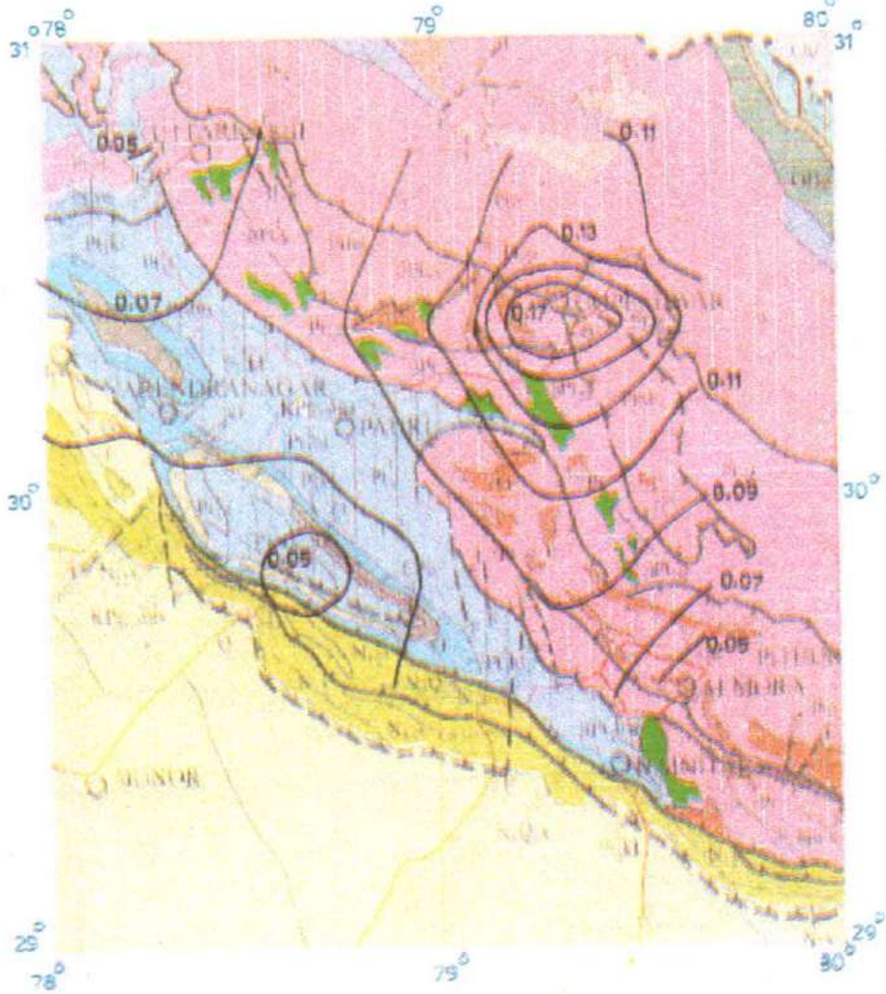


Fig. 3 Contours of largest recorded PGA during Chamoli earthquake, March 29, 1999

Fig. 4 Strong ground motion time history, Chamoli earthquake, March 29, 1999
Station: Gopeshwar 30^0 24' N 79^0 20' E Comp : Long (N70W)
Peak values : Acc. = 195.08 cm/s*s; Vel. = 22.55 cm/s; Disp. = 5.22 cm

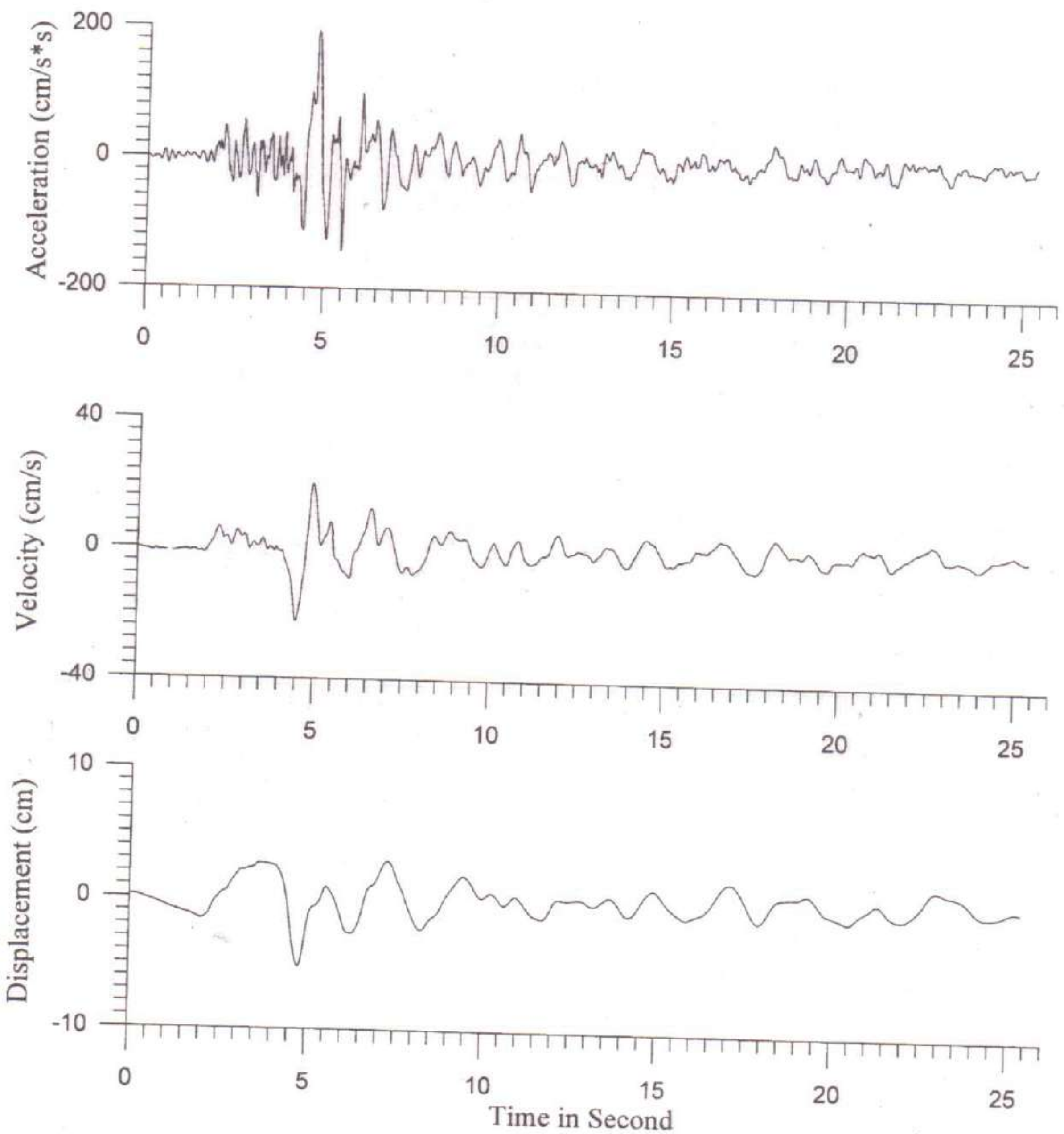


Fig. 5 Strong ground motion time history, Chamoli earthquake, March 29, 1999
Station: Gopeshwar 30^0 24' N 79^0 20' E Comp : Trans (N20E)
Peak values : Acc. = 352.83 cm/s*s; Vel. = 45.31 cm/s; Disp. = 12.28 cm

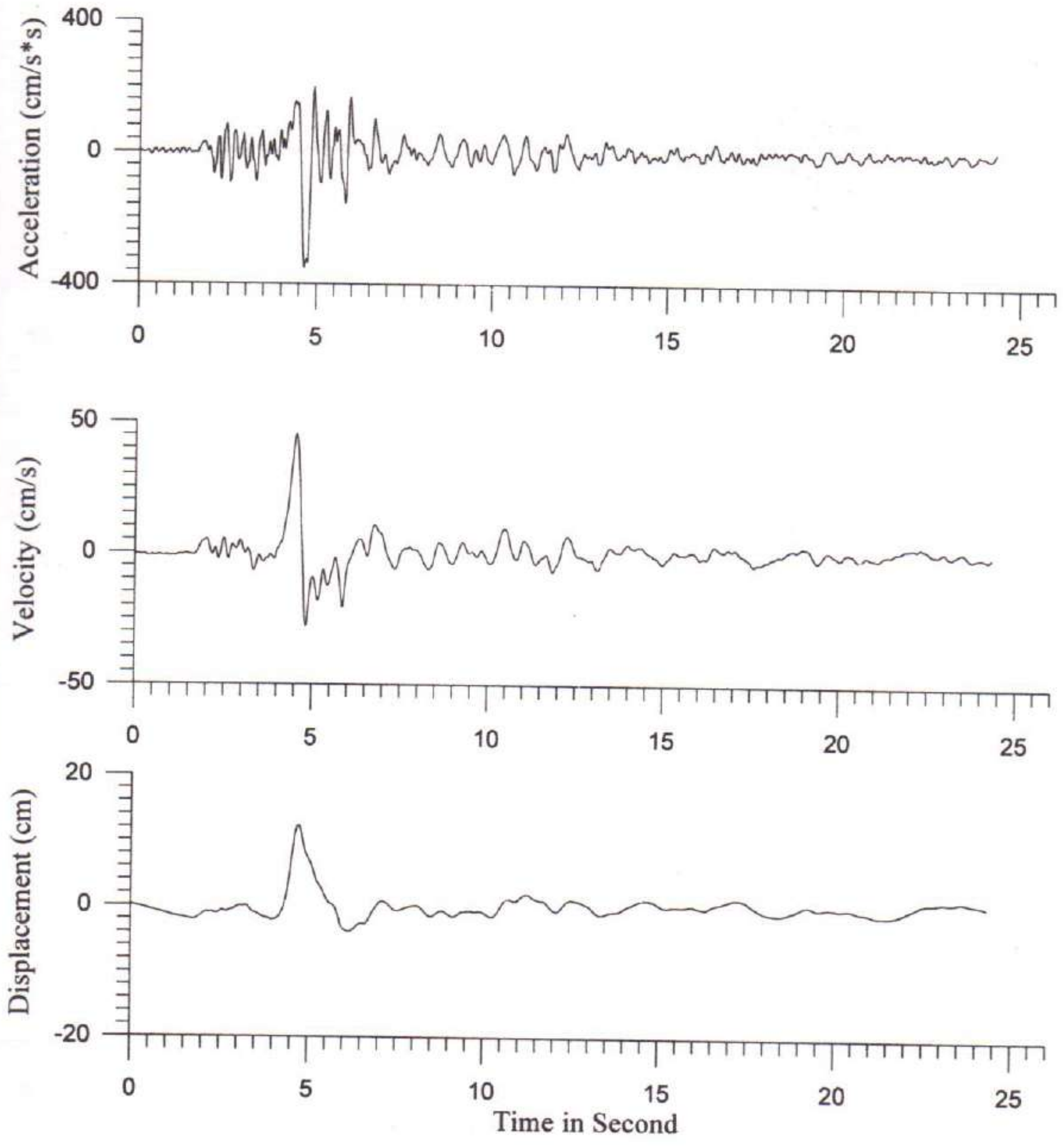


Fig. 6 Strong ground motion time history, Chamoli earthquake, March 29, 1999
Station: Gopeshwar 30^0 24' N 79^0 20' E Comp : Vert
Peak values : Acc. = 153.73 cm/s*s; Vel. = 7.50 cm/s; Disp. = 2.09 cm

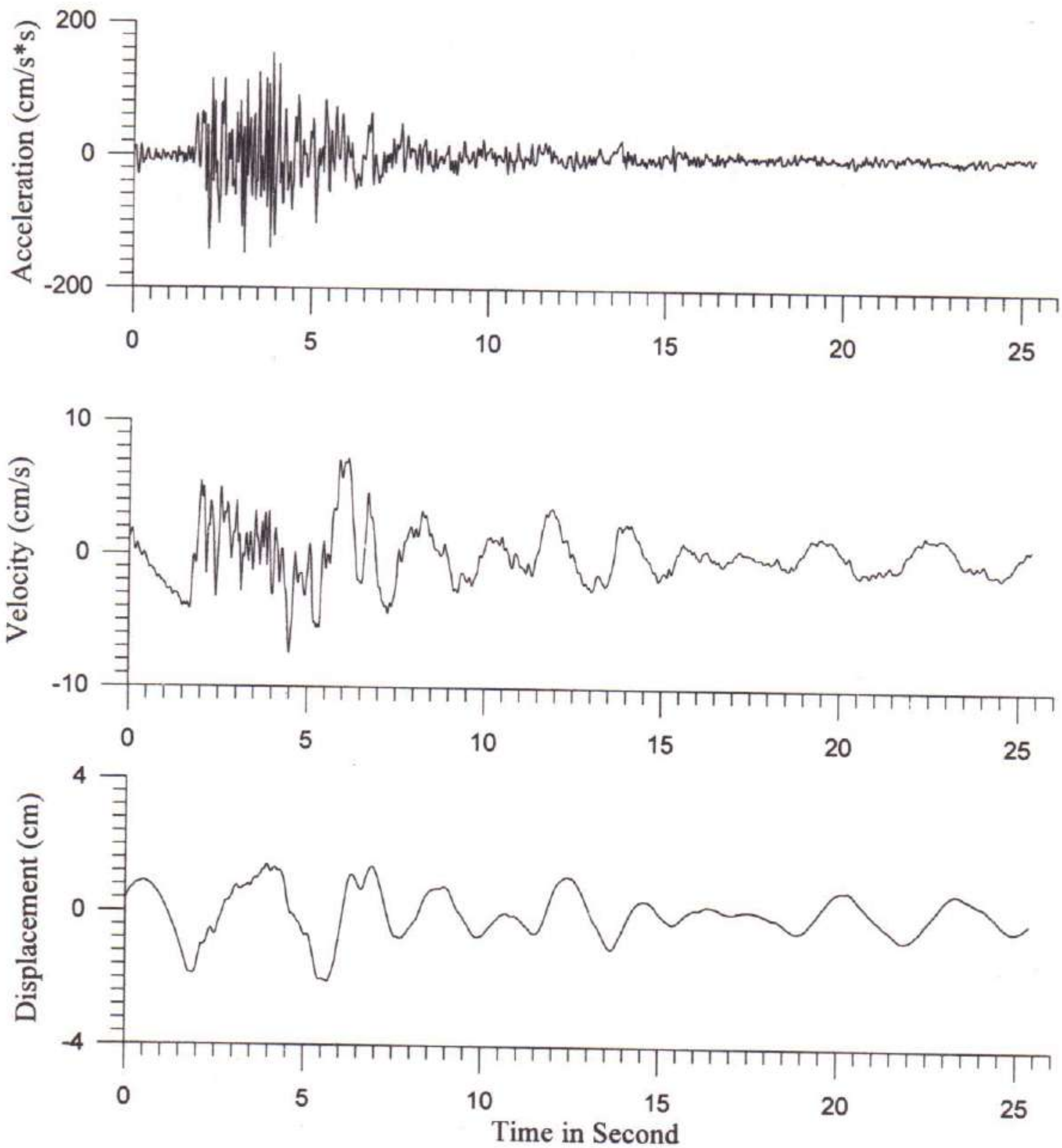
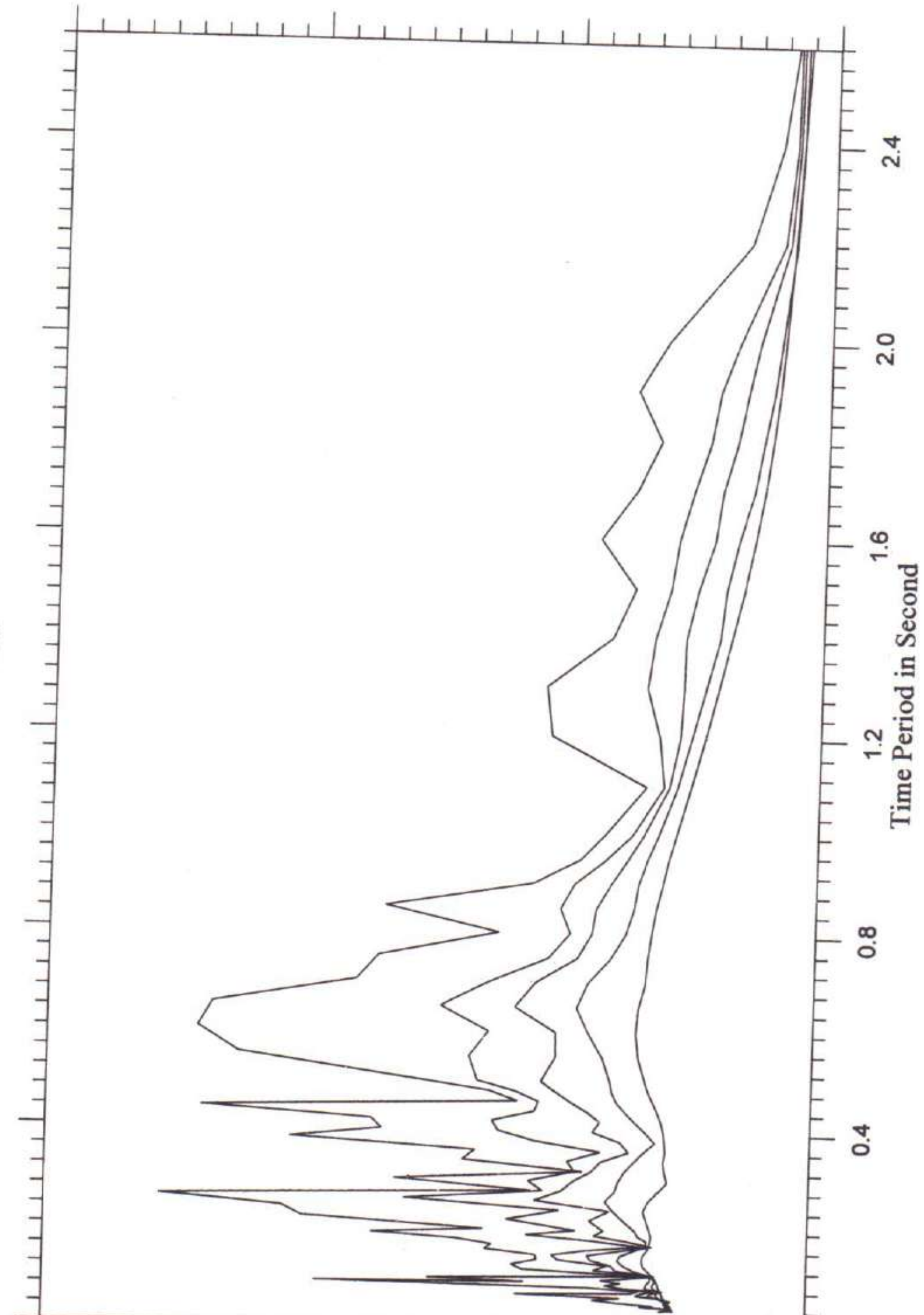


Fig. 7 Response spectra of Chamoli earthquake, March 29, 1999
Station: Gopeshwar 30° 24' N 79° 20' E Comp : Long (N70W)
Damping - 0, 2, 5, 10 & 20 % of critical



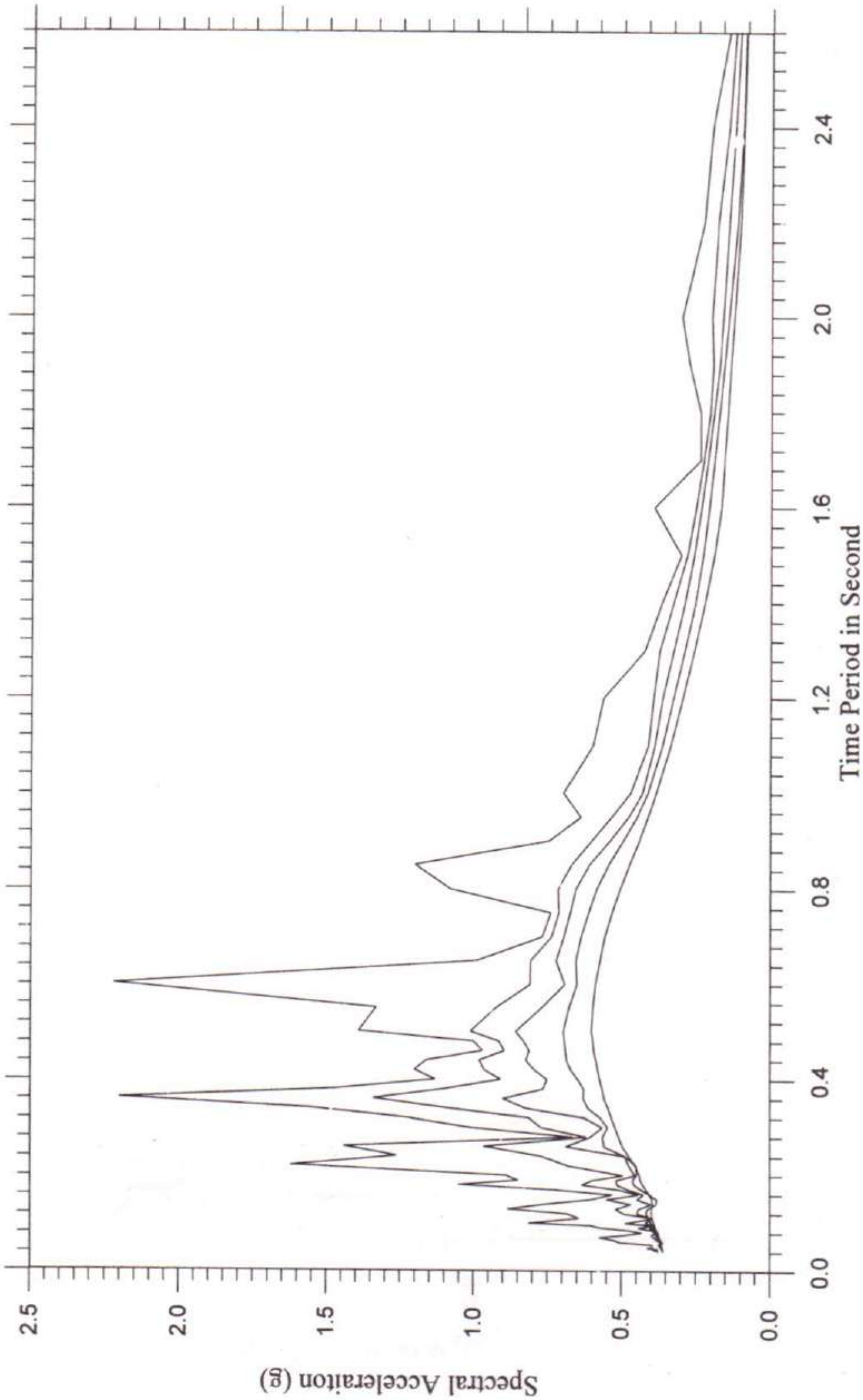
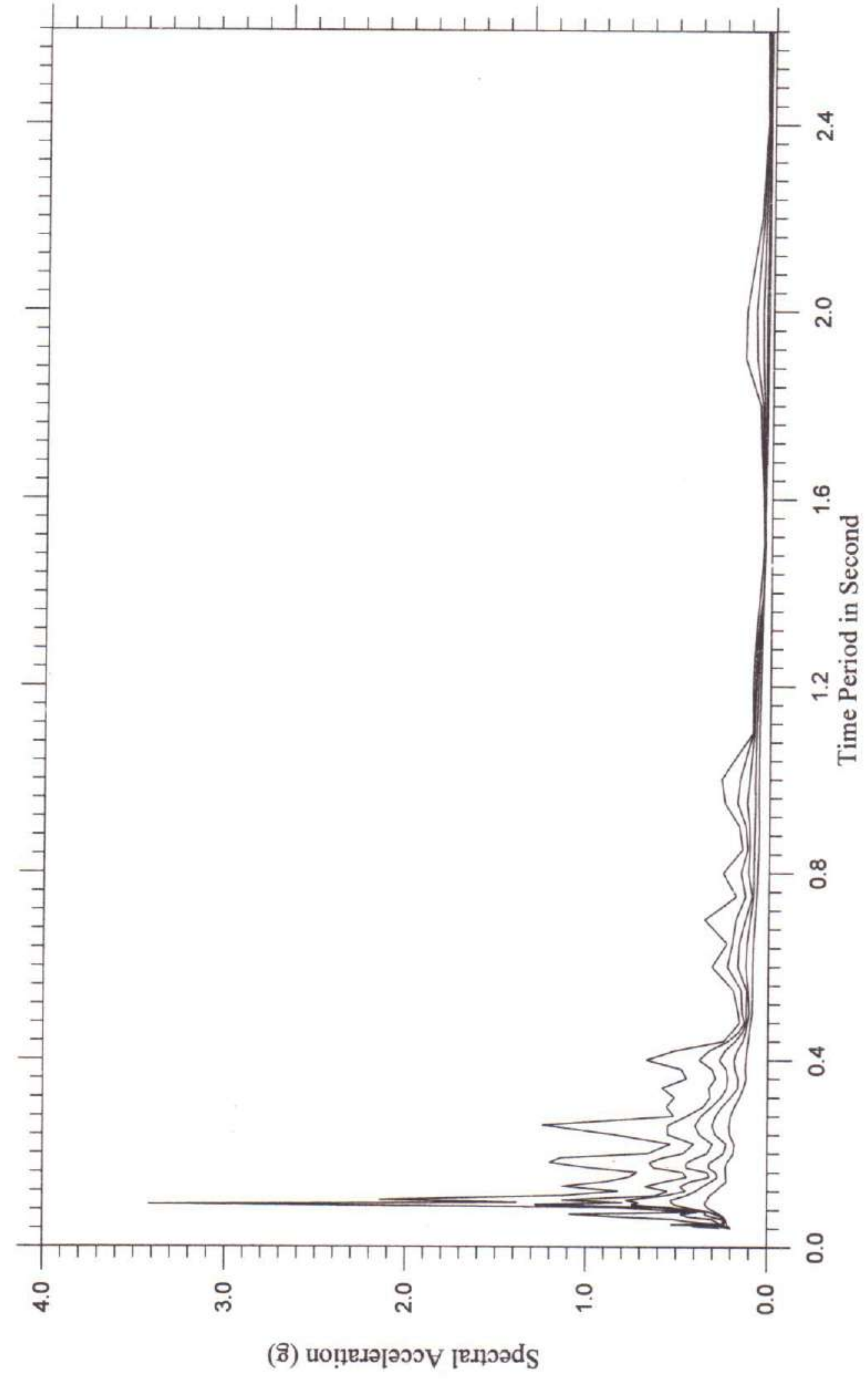


Fig. 8 Response spectra of Chamoli earthquake, March 29, 1999
Station: Gopeshwar 30° 24' N 79° 20' E Comp : Trans (N20E)
Damping - 0, 2, 5, 10 & 20 % of critical

Fig. 9 Response spectra of Chamoli earthquake, March 29, 1999
Station: Gopeshwar 30° 24' N 79° 20' E Comp : Vert
Damping - 0, 2, 5, 10 & 20 % of critical



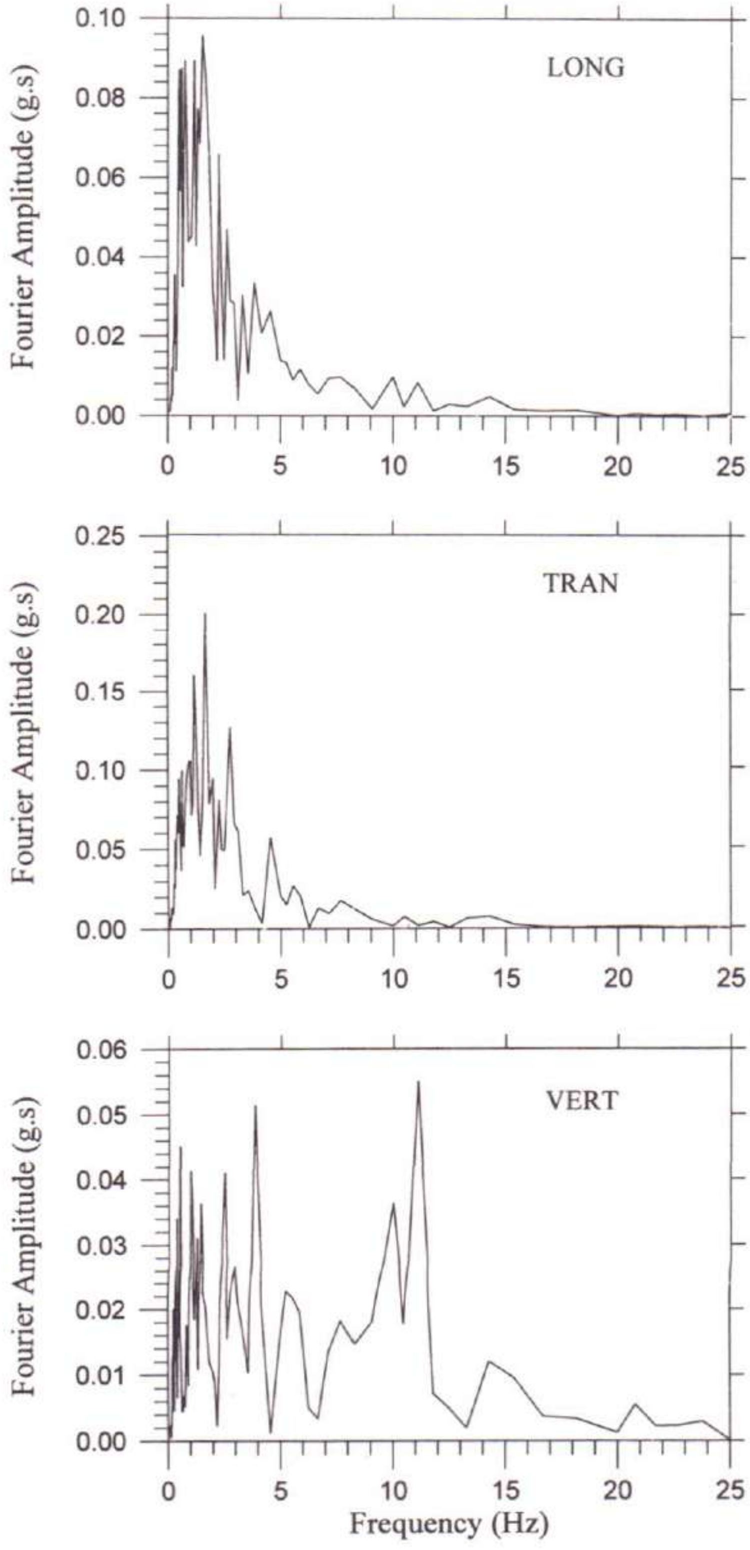


Fig. 10 Fourier amplitude spectra of acceleration time histories recorded at Gopeshwar

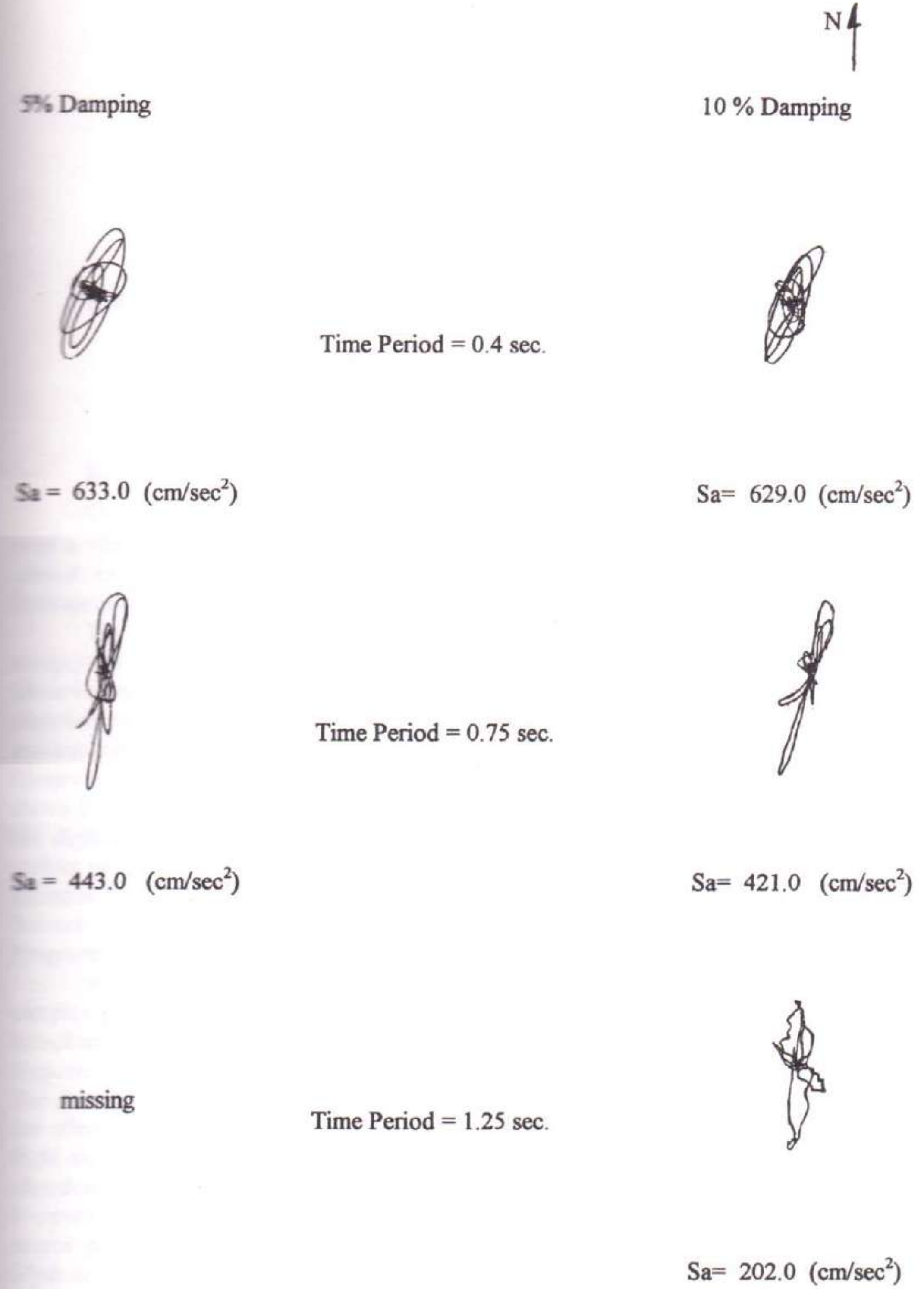


Fig. 11 Records of SRR and computed spectral acceleration at Gopeshwar.
Chamoli earthquake, March 29, 1999

Chapter 3

BROADBAND SEISMIC RECORDING

H.R.Wason, M. L. Sharma, P. K. Khan, K. Kapoor, D. Nandini and V. Kara

Introduction

The main shock and some of the aftershocks of Chamoli earthquake were felt over a very large area in Uttar Pradesh, Delhi and adjoining states. The earthquake caused extensive damage to the public property, mostly in the Chamoli and Rudraprayag districts and more than 100 persons lost their lives.

The main shock and the aftershocks have been very well recorded by a 3-component broadband Seismograph deployed at Narendranagar Seismological Observatory. The source region of the Chamoli earthquake is about 100 km in the NE direction of this Observatory. The aftershock sequence has also been recorded on another broadband Seismograph installed at Nainital in the complex of U.P. State Observatory from March 30, 1999 onwards. More than 100 aftershocks with magnitude above 2.0 were recorded by the two broadband Seismographs till April 26, 1999. Both the digital broadband Seismograph stations are being operated under the research project entitled "Modelling of Earthquake Source and Earth Structure in the Garhwal Kumaon Himalaya Region using Broadband Seismic Data", funded by Department of Science & Technology, Govt. of India under its "All India Himalayan Seismicity Programme".

All the earthquake events were recorded in triggered mode at the rate of 100 samples per second per channel. This report presents a preliminary analysis of the broadband seismic data of the main shock and aftershocks of the earthquake. Hypocentral parameters of the main shock and 51 aftershocks have been determined. The distribution of the epicenters and two depth sections of 51 hypocenters show that the aftershock activity has been concentrated between MBT and MCT, close to the Birhi and Alaknanda rivers, to the south of main shock. The source parameters of the aftershocks analysed in this report are also estimated from the displacement spectra of P-waves based on the approach given by Brune (1970). The changes in the values of source parameters are analysed with respect to magnitudes, time of occurrence and depth of events, respectively.

Seismotectonics of the region

This earthquake occurred in the Garhwal Lesser Himalaya region which forms part of the plate boundary between the colliding Indian and the Eurasian plates. The region is characterised by three major northward dipping thrust zones separated by geological/physiographic sub provinces. The northernmost sub province is the Greater Himalaya which has an average elevation of 5 km and is composed of crystalline metamorphic and igneous rocks brought up along the Main Central Thrust (MCT). The sedimentary rocks in the south, which are mostly of Paleozoic age, define the Lesser Himalaya sub province, which is delimited by the Main Boundary Thrust (MBT) to its south. These slightly metamorphosed sediments are overlain, in places, by a thrust sheet of the crystalline rocks. The average elevation in this part is about 2.5 km. South of MBT lies Outer Himalaya or Sub-Himalaya region with elevation of a few hundred meters. This region consists of folded and faulted Siwalik mollase sediments of Miocene age (Valdiya, 1988).

In the most widely accepted tectonic model, a detachment of fault represents the top surface of the northward underthrusting Indian plate over which the wedges of Himalaya rock units are thrusted southward. The detachment fault represent a decollement dipping gently below the Outer and Lesser Himalaya at depths of about 15-20 km. The detachment fault is imaged at a depth of about 30 km in southern Tibet north of Higher Himalaya (Seeber et al., 1981). The seismic activity in this region is largely concentrated in a relatively narrow belt, with a majority of events occurring primarily south of the surface trace of the MCT. Most of these earthquakes have focal depths in the upper 20 km of the crust. Majority of earthquakes are located between part of Lesser Himalaya and immediate south of Higher Himalaya extending from Nepal through Kumaon and Garhwal and western Himachal Pradesh (Ni and Barazangi, 1984). The epicenteral zone of the Chamoli earthquake of March 29, 1999, is located in the inner Lesser Himalaya zone just south of the surface trace of the Main Central Thrust.

Broadband seismograph stations

Two broadband Seismograph stations are deployed in the Lesser Himalaya at Narendranagar and Nainital. The Broadband seismograph station at Narendranagar (30.15°N, 78.28°E) is deployed in a Seismological Observatory of the U.P. Irrigation Department with pier situated on Quartzite. The Seismograph station at Nainital is located in the complex of the U.P. State Observatory (29.41°N, 79.70°E). The broadband sensor is placed on a pier situated on the krol beds.

The instrumentation at each station consists of triaxial broadband seismometer (CMG-40T), Reftek high resolution (24-bit) data acquisition system, GPS for time stamping of samples and 12-volt power supply. The triaxial broadband sensor provides velocity response flat in the frequency range of 20 sec to 50 Hz. The dynamic range of the Seismograph system is 130 dB at 50 Hz. The digital data has been recorded in triggered mode with sampling rate of 100 samples per second per component. The digital broadband waveforms of the Chamoli earthquake recorded at Narendranagar station are shown in Fig. 1.

Hypocentral parameters of the Chamoli earthquake

The hypocenteral parameters of the Chamoli earthquake have been determined using HYPO71 program (Lee and Lahr, 1975). To locate the earthquake, the phase data (P- and S-arrival times) from Narendranagar broadband station is augmented by phase data for few other distant stations. A total of 7 phases from 5 stations are used for location of this earthquake. The hypocenteral parameters of the main shock thus computed along with those reported by USGS and IMD are given in Table I.

Table I. Hypocentral Parameters of the Chamoli Earthquake

Source	Date	Origin Time	Lat. (°N)	Long. (°E)	Depth (km)	Mag.
IMD	28-03-1999	190512.00	30° 18'	79° 34'	21	6.8
USGS	28-03-1999	190510.00	30° 25'	79° 13'	15	6.4
Present Study	28-03-1999	190511.25	30° 26'	79° 28'	18	6.7

The epicenter of the Chamoli earthquake lies on the boundary of autochthonous zone and Ramgarh Nappe as can be seen in Fig. 2.

Aftershock activity

A total of 106 aftershocks with magnitude, M_L>2.0 were recorded at the two broadband seismic stations upto 26th April, 1999. The variation of magnitudes of 106 aftershocks with time is shown in Fig. 3. The hypocenteral parameters of 51 aftershocks have been determined using HYPO71 PC Program (Lee and Lahr, 1975). It is observed that the aftershock activity is mainly distributed to the south of the main shock in the vicinity of Birhi and Alaknanda rivers as can be seen from the epicenters marked in Fig. 2. The velocity model used in the present analysis consists of two layer model over a half space. The P-wave velocities have been assumed to be 5.72 km/sec and 6.62 km/sec for the upper 24 km and 21 km thick layers respectively. The P-wave velocity for the half space below these two layers is taken as 8.22 km/sec (IMD, 1999). The hypocenteral parameters and magnitudes determined for 51 aftershock events are listed in Table II.

Table II. Hypocentral parameters and magnitude of the aftershocks.

Event No.	Date	Origin Time Hr. Min. Sec.	Mag. (M_L)	Lat. (°N)	Long. (°E)	Depth (km)
1	28-03-99	20:38:58.73	3.5	30.46	79.33	9.9
2	28-03-99	21:21:17.43	3.2	30.50	79.22	20.9
3	28-03-99	21:24:46.57	3.2	30.36	79.39	8.5
4	28-03-99	21:42:53.51	3.8	30.19	79.27	14.6
5	28-03-99	21:57:12.04	3.0	30.36	79.34	15.6
6	28-03-99	22:56:06.05	3.7	30.50	79.29	6.3
7	28-03-99	23:01:40.76	4.2	30.39	79.39	8.7
8	28-03-99	23:20:30.11	4.2	30.37	79.36	20.3
9	28-03-99	23:44:36.34	2.9	30.44	79.18	8.9
10	28-03-99	23:55:15.08	3.4	30.48	79.33	11.7

Contd..

11	29-03-99	00:22:48.70	4.2	30.41	79.34	16.5
12	29-03-99	03:46:31.82	3.3	30.50	79.42	14.4
13	29-03-99	04:17:14.88	3.5	30.25	79.29	20.1
14	29-03-99	05:55:41.67	3.2	30.29	79.33	8.5
15	29-03-99	06:55:30.50	3.2	30.20	79.47	22.4
16	29-03-99	07:51:57.67	2.7	30.21	79.18	5.4
17	29-03-99	08:49:49.11	4.7	30.23	79.31	16.0
18	29-03-99	09:19:55.53	3.8	30.29	79.11	15.5
19	29-03-99	09:39:15.94	3.3	30.24	79.36	16.0
20	30-03-99	15:51:52.39	4.1	30.41	79.40	25.1
21	30-03-99	21:02:14.27	5.1	30.32	79.34	16.3
22	31-03-99	08:40:04.26	3.6	30.43	79.35	15.4
23	31-03-99	16:04:49.48	3.7	30.23	79.30	17.7
24	31-03-99	20:39:52.37	3.1	30.29	79.31	09.5
25	01-04-99	02:48:58.12	3.9	30.12	79.24	09.3
26	01-04-99	07:19:12.14	3.9	30.39	79.39	05.4
27	02-04-99	22:42:54.27	2.8	30.30	79.26	19.5
28	06-04-99	19:37:26.39	5.5	30.40	79.38	08.3
29	06-04-99	22:52:16.12	3.0	30.38	79.36	07.1
30	06-04-99	23:55:57.73	3.3	30.36	79.43	03.0
31	07-04-99	15:49:15.37	4.9	30.42	79.39	05.9
32	07-04-99	16:23:29.65	4.5	30.37	79.36	06.2
33	07-04-99	17:18:20.16	3.1	30.37	79.40	04.5
34	07-04-99	18:49:28.25	3.0	30.38	79.40	0.4
35	07-04-99	19:01:45.26	3.4	30.45	79.39	03.5
36	07-04-99	22:10:36.29	3.1	30.44	79.32	06.9
37	07-04-99	22:34:21.85	2.8	30.34	79.34	01.1
38	10-04-99	16:15:03.03	3.1	30.42	79.40	01.9
39	12-04-99	08:11:58.52	2.9	30.24	79.29	16.8
40	12-04-99	13:03:38.14	3.7	30.34	79.29	14.8
41	12-04-99	14:11:27.98	3.8	30.33	79.25	08.0
42	14-04-99	17:24:31.85	5.2	30.24	79.38	23.1
43	15-04-99	12:01:32.42	3.2	30.39	79.40	08.0
44	15-04-99	13:01:25.51	2.8	30.31	79.31	04.1
45	16-04-99	17:22:09.32	3.4	30.25	79.38	14.6
46	18-04-99	17:16:40.82	4.7	30.33	79.32	07.6
47	18-04-99	21:21:46.08	2.7	30.31	79.30	10.2
48	22-04-99	05:07:43.96	2.9	30.30	79.29	13.0
49	22-04-99	14:48:30.14	3.3	30.25	79.46	10.5
50	25-04-99	09:52:15.14	3.9	30.41	79.40	01.5
51	26-04-99	01:07:34.73	3.2	30.23	79.20	11.0

Two depth sections of the hypocenters, one (Fig. 4a) in a direction N30°E and another (Fig. 4b) along N120°E have been drawn taking the origin at Lat. 29.33°N, Long.78.75°E and Lat.30.36°N, Long. 78.75°E, respectively. The first depth section is oriented parallel to the trend of Birhi river whereas the second section intersects this river perpendicularly near Chamoli which is at about 70 km away from its origin.

Computation of source parameters

Source parameters viz., seismic moment, stress drop and source radius of aftershock events analysed in this report have been determined from the P-wave spectra using Brune's model (Brune, 1970). After removing the DC bias of the instrument, geometrical spreading correction has been applied on the raw data. A 5.12 sec window (512 samples at 100 samples per sec) from the start of P-wave is taken to compute P-wave spectra. The sample window is then cosine tapered with a 10% taper at both the ends. The Fast Fourier Transform (FFT) algorithm of Cooley and Tukey was applied to compute the signal spectrum. The corner frequency and low frequency asymptote are then estimated from the computed Fourier spectra of the P-wave by eye fitting.

Once the corner frequency and low frequency spectral levels are known, the source parameters can be estimated using Brune's model. The source parameters of the 51 aftershock events have been computed from the spectral analysis using the formulations as follows:

$$M_0 = 4\pi\rho v^3 D\Omega_0 / R_{\theta\varphi}, \text{ where } R_{\theta\varphi} = \sqrt{2/5} \quad (1)$$

$$r = 2.34v / 2\pi f_c \quad (2)$$

$$\Delta\sigma = 7M_0 / 16r^3 \quad (3)$$

where M_0, ρ, v, r, f_c, Δσ, D, Ω_0 and $R_{\theta\varphi}$ denote seismic moment, density at the source, P-wave velocity at the source, source radius, corner frequency, stress drop, epicenteral distance, low frequency spectral level of P-wave and radiation pattern, respectively. The estimated values for the source parameters are given in Table III .

Table III. Source parameters of the aftershocks.

Event No.	Seismic Moment (Dyne-cm)	Source Radius (m)	Stress Drop (Bars)
1	2.96 E+20	289.55	5.33
2	7.22E+19	272.52	1.56
3	3.03E+20	289.55	5.46
4	1.05E+21	289.55	18.97
5	2.91E+20	386.07	2.21
6	6.20E+20	308.86	9.20
7	2.19E+21	421.17	12.80
8	2.13E+21	356.37	20.58
9	7.95E+19	257.38	2.03
10	3.36E+20	289.55	6.05
11	2.23E+21	386.07	16.90

Contd...

12	5.92E+20	308.86	8.79
13	5.45E+20	330.92	6.57
14	7.11E+20	386.07	5.40
15	4.78E+20	272.52	10.33
16	4.81E+19	243.83	1.45
17	4.86E+21	463.29	21.37
18	1.00E+21	386.07	7.62
19	3.61E+20	331.03	4.35
20	2.02E+21	579.11	4.55
21	3.76E+22	1007.16	16.11
22	5.69E+20	463.29	2.50
23	5.20E+20	386.07	3.95
24	3.07E+20	386.07	2.33
25	1.54E+21	463.29	6.77
26	9.87E+20	579.11	2.22
27	1.87E+20	421.17	1.10
28	4.72E+22	827.31	36.4
29	8.90E+19	330.92	1.07
30	6.33E+20	463.29	2.78
31	1.47E+22	681.31	20.30
32	7.43E+21	503.58	25.40
33	3.10E+20	386.07	2.35
34	1.86E+20	386.07	1.41
35	3.12E+20	386.07	2.37
36	4.12E+20	386.07	3.13
37	1.44E+20	330.92	1.73
38	2.03E+20	356.37	1.96
39	1.76E+20	330.92	2.12
40	4.54E+20	330.92	5.48
41	5.29E+20	330.92	6.38
42	2.95E+22	681.31	40.80
43	4.95E+20	330.92	5.97
44	1.40E+20	289.55	2.52
45	5.94E+21	421.17	3.47
46	1.14E+22	609.59	22.00
47	1.38E+20	289.55	2.48
48	1.36E+20	386.07	1.03
49	5.61E+20	386.07	4.26
50	1.56E+21	421.17	9.13
51	2.49E+20	289.55	4.48

The Fourier displacement spectra for 11 aftershocks with magnitude, $M_L \geq 4.0$ are shown in Fig. 5. The vertical components of the displacement waveform are also shown. The shallow aftershock events are found to be having low stress drop values ranging between 1 bar and 41 bars. The source radius varies between 243 m. to about 1 km. The plots of the source parameters namely, seismic moment, radius and stress drop with respect to depth (Fig. 6) reveal no correlation. The scatter of the source parameters may be attributed to the poor control in the computation of depth and the fewer number of stations data used for location. Similar exercise carried out for looking into the variation of source parameters with respect to time shows that the scatter is too much and there is no correlation between the two (Fig. 7).

The empirical relationships computed between the Richter magnitude (M_L) and the source parameters based on linear regression analysis (Fig. 8) are as follows:

$$\log(M_0) = (0.9605 \pm 0.0519)M_L + (17.410 \pm 0.189) \quad (4)$$

$$\log(r) = (0.146 \pm 0.017)M_L + (2.066 \pm 0.062) \quad (5)$$

$$\log(\Delta\sigma) = (0.531 \pm 0.045)M_L - (1.196 \pm 0.163) \quad (6)$$

Discussion and conclusions

The hypocenteral parameters of the Chamoli earthquake of March 29, 1999 have been computed as: Lat. 30° 26′N, Long. 79° 28′E, focal depth 17.7 km and origin time 99 03 29 00 35 11.25 (IST). A total of 106 aftershocks with magnitude>2.0 were recorded at the two broadband seismograph stations till April 26, 1999. The temporal variation of magnitude of aftershocks indicates that the earthquake activity was quite intense in the first three days and then decayed with time. It is also evident from the nature of the graph that the seismic energy has been released periodically and in each period the occurrence of maximum magnitude decayed almost exponentially.

The distribution of the epicenters and depth sections of 51 hypocenters shows that the aftershock activity has been concentrated between MBT and MCT, close to the Birhi and Alaknanda rivers, to the south of main shock. The source parameters of 51 aftershock events have been computed from the Fourier spectra of P-waves based on Brune's model. The seismic moment of the aftershocks is computed to be between 4.81×10^{19} and 4.72×10^{22} dyne-cm and their source radius vary between 243 m to 1 km. The aftershock events have low stress drop values between 1 bar to 41 bars. Similar observation of low stress drop values for local earthquakes in this region were also reported earlier by Sharma and Wason (1994).The low stress drop values at shallow depths indicate that the rock mass constituting the upper crust in the region has low strength for accumulation of strain and the rocks undergo brittle fractures and adjustments. Logarithms of the source radius, seismic moment and stress drop appear to be linearly related with the magnitude of the earthquake events. However, no correlation were observed in the source parameters with respect to time and depth.

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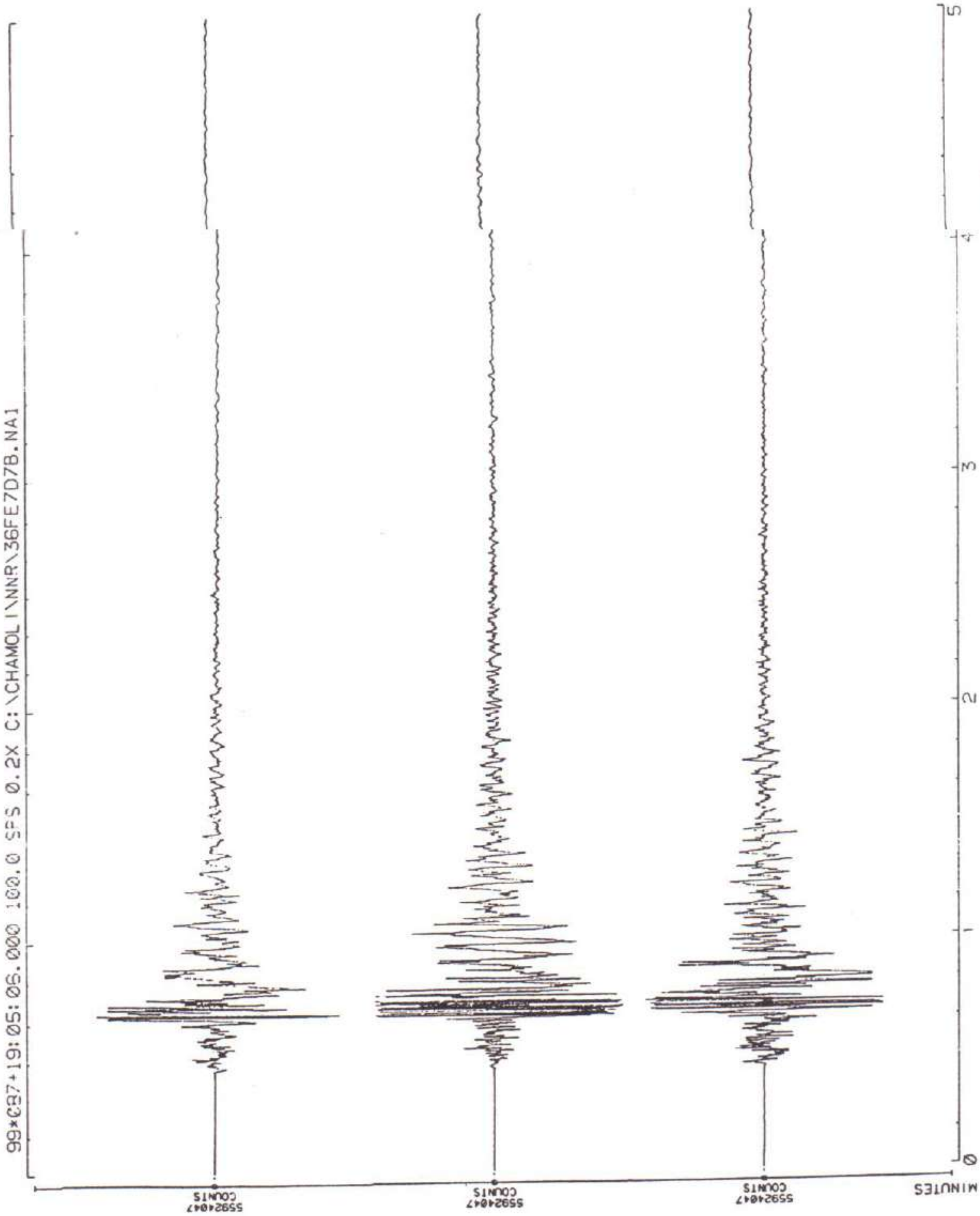


Fig.1. Broadband waveform traces (V-, N-S & E-W) of the Chamoli earthquake of March 29, 1999 recorded at Narendranagar station.

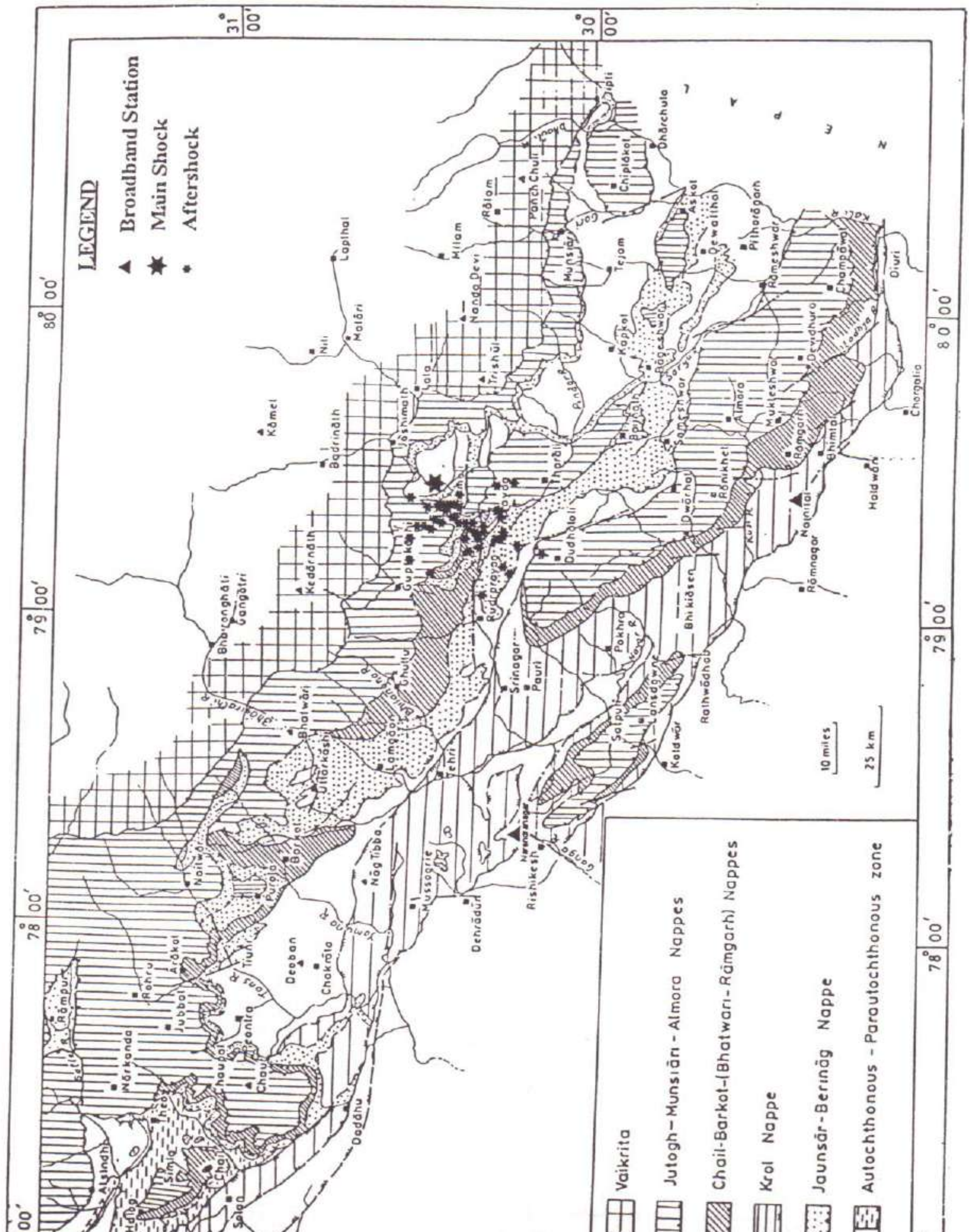


Fig.2. Tectonic map (afterValdiya, 1975) of the region showing epicentres of the Chamoli earthquake of March 29, 1999 and 51 aftershocks.

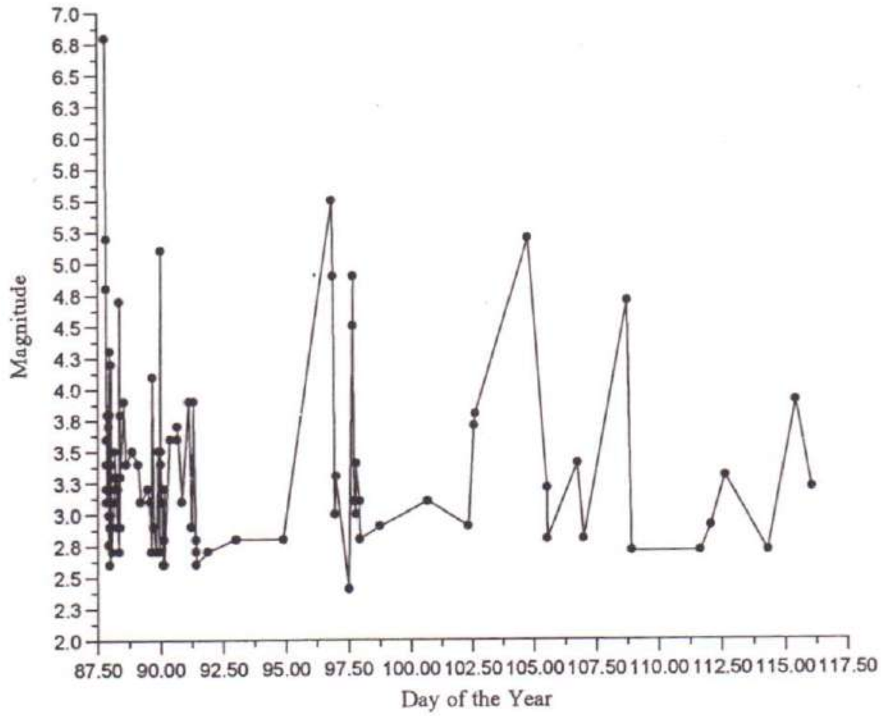
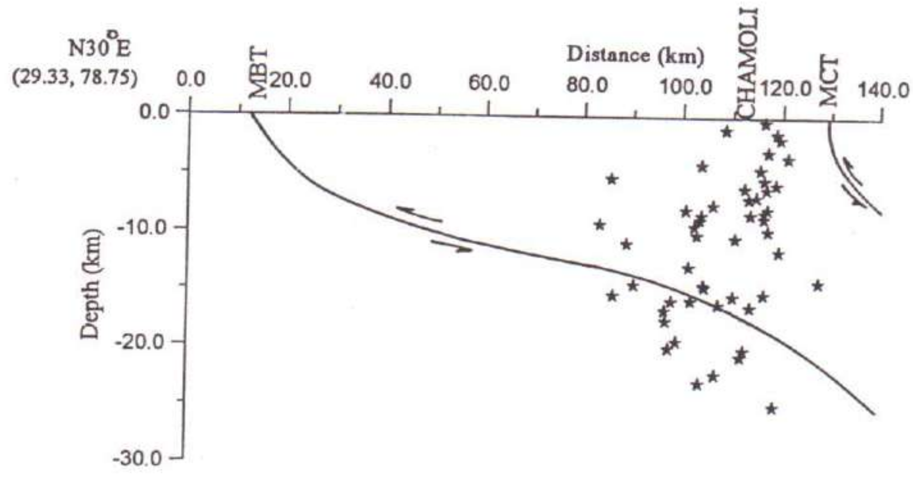
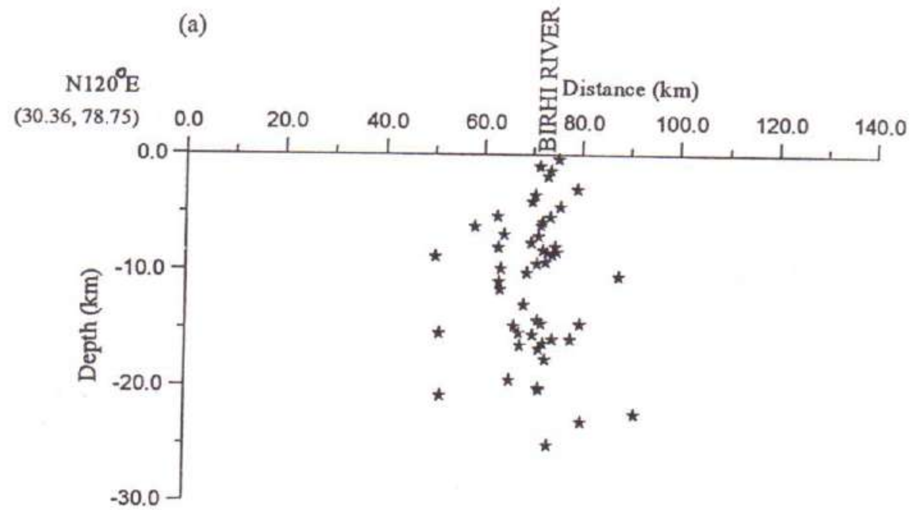


Fig.3. Plot showing the variation of magnitudes of the aftershocks with time.

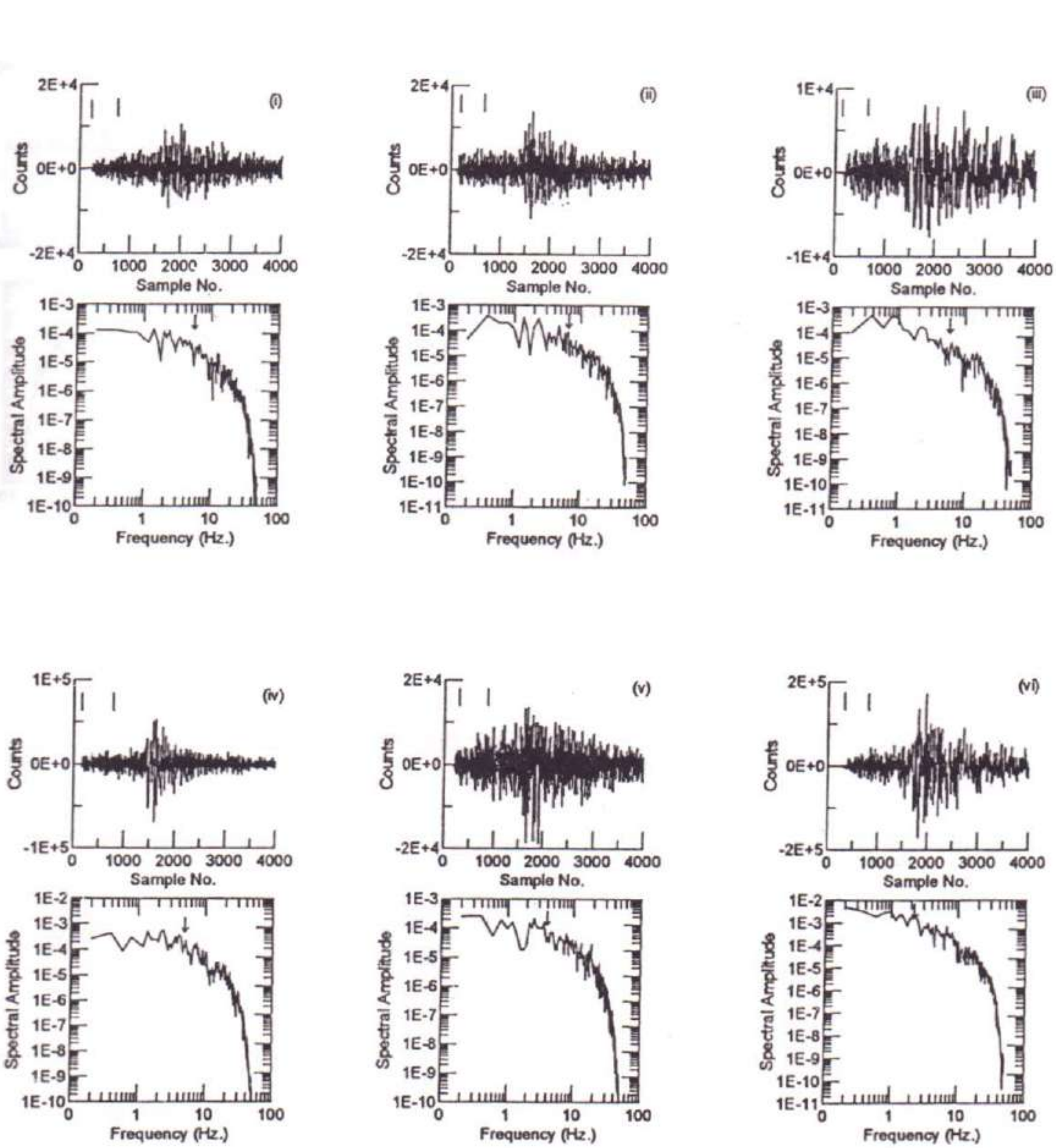


(a)



(b)

Fig.4. Diagrams showing the depth sections of the hypocentres, a) one in a direction N30°E,and b) another along N120°E taking the origin at 29.33°N, 78.75°E and 30.36°N, 78.75°E, respectively.


(i)
(ii)
(iii)
(iv)
(v)
(vi)
Counts
Sample No.
Spectral Amplitude
Frequency (Hz.)
0 1000 2000 3000 4000
0 1 10 100

Contd...

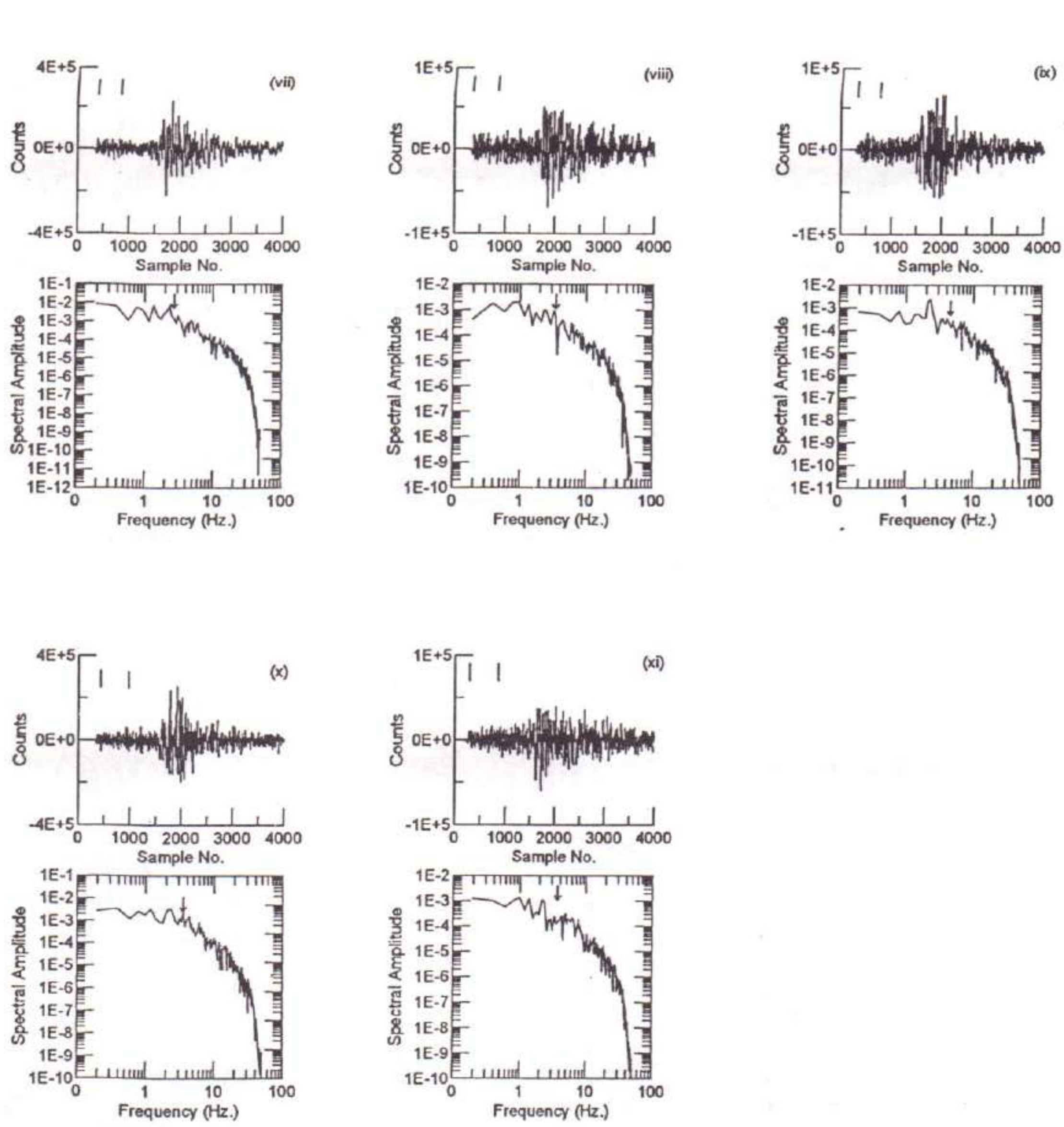


Fig.5. Diagrams showing the Fourier displacement spectra for the vertical component of P-wave of 11 aftershocks with magnitude, $M_L \geq 4.0$.

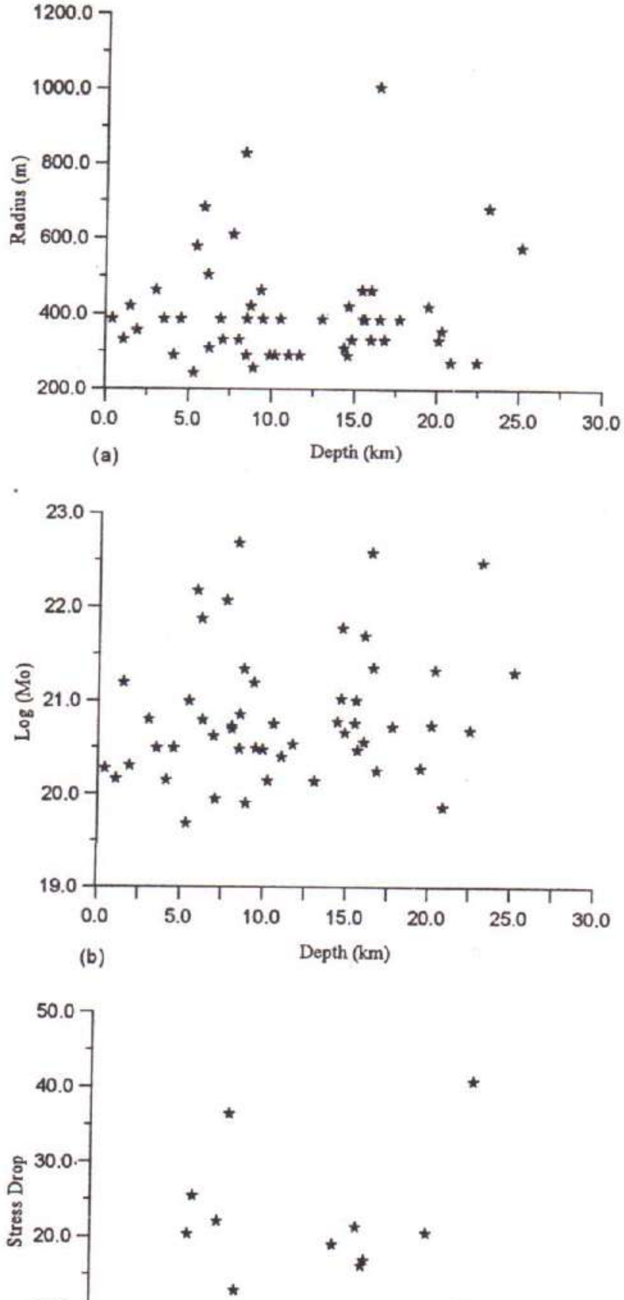


Fig. 6. The plots showing the variation of (a) Source Radius, (b) Seismic Moment and (c) Stress Drop with Depth.

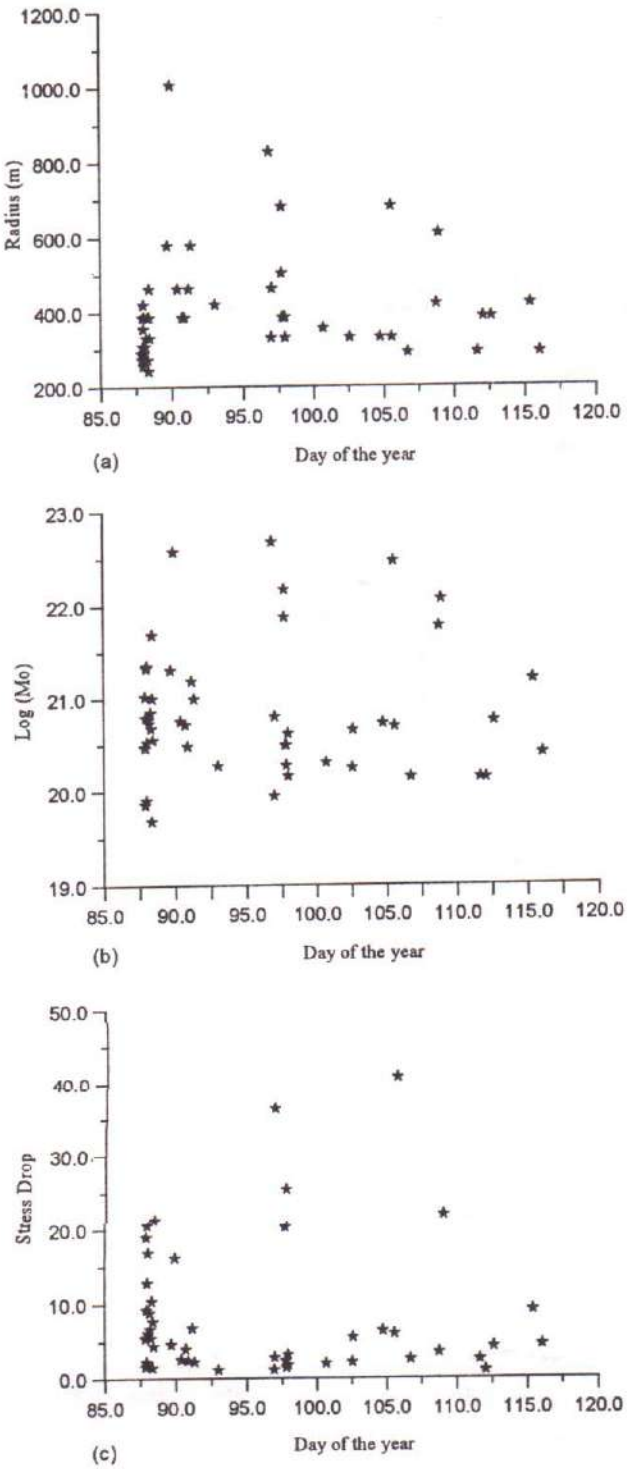


Fig.7. The plots showing the variation of (a) Source Radius, (b) Seismic Moment and (c) Stress Drop with Time.

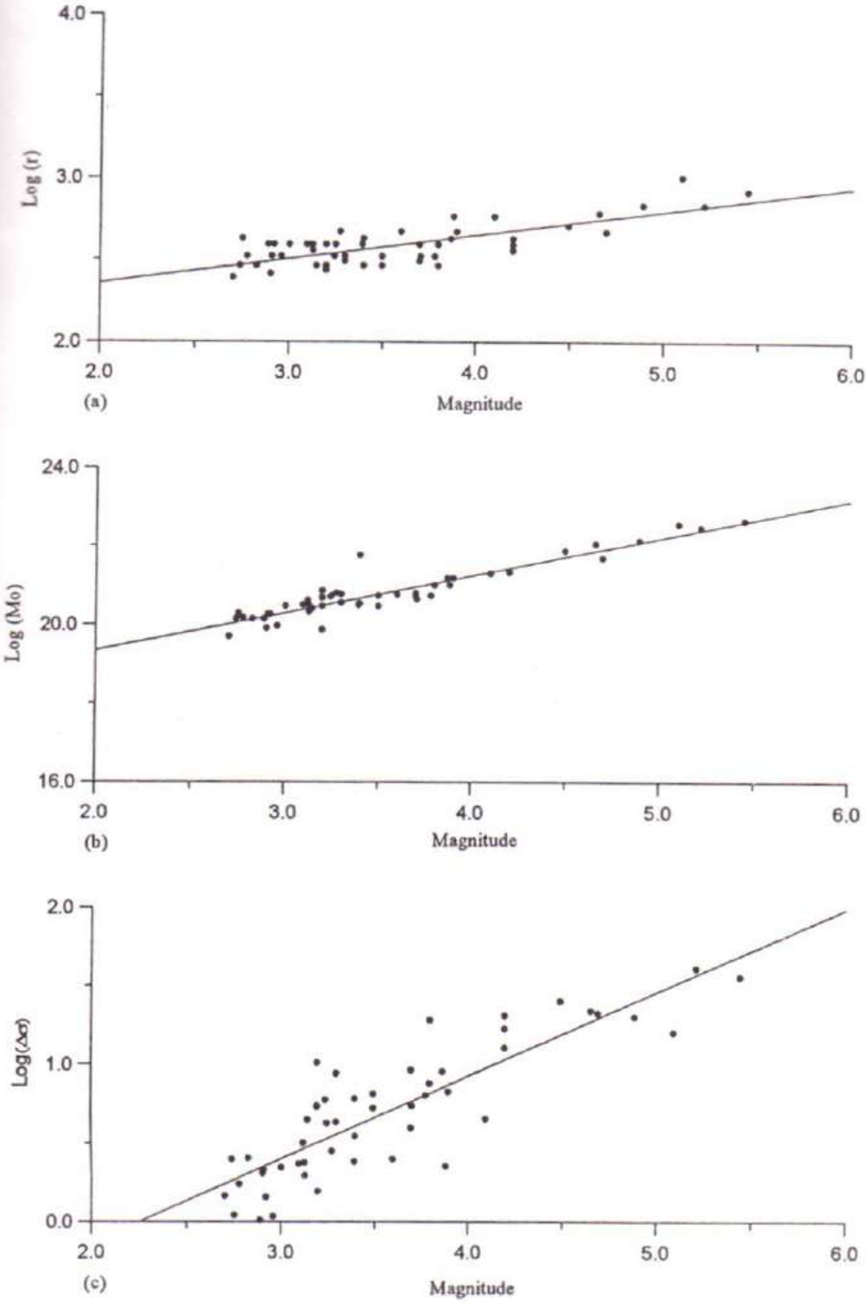


Fig.8. The semi-log plots showing the variation of (a) Source Radius, (b) Seismic Moment and (c) Stress Drop with Magnitude.

Chapter 4

PERFORMANCE OF BUILDINGS & BRIDGES

Durgesh C. Rai

Introduction

This chapter describes the effect of strong ground motion on the built environment, especially buildings and bridges during the Chamoli earthquake. The chapter provides a critical appraisal of seismic resistance of widely practiced construction techniques by studying the differences between the observed and the expected behaviour and damage pattern of the constructed facilities. The structural deficiencies of these construction types have been identified which led to their unsatisfactory response and widespread damage. Non-compliance to the earthquake-resistant construction features, as well as poor construction practices for locally available building materials were responsible for the majority of structural damage observed in the earthquake-affected area.

Building types

Majority of buildings are box type (load bearing stone, brick or concrete block masonry) and have suffered more damage than RC framed (with infills) types which, though very few in number, have performed extremely well, even in the regions of high shaking. The seismic performance of load bearing masonry structures depend heavily on the structural characteristics (strength, stiffness and ductility) of surrounding walls to resist in-plane and out-of-plane inertia forces and of the diaphragms (floors & roofs) to not only safely resist the shear forces but also to distribute the forces to vertical elements (walls) and maintain the integrity of the structure. Various types of material and construction techniques for walls and diaphragms have been prevalent in the affected regions, which can be classified in the following categories:

Stone Masonry

Stone masonry is produced from a wide range of materials and constructed in many different forms which have shown varying degree of performance in the Chamoli earthquake. Unreinforced stone masonry is very durable even in the hostile environment and has accommodated movements and resisted natural forces without becoming unstable and falling apart. Common rock types which are used for building construction in the affected region are sandstone, limestone, quartzite and slate, which are internally very durable building materials. However, some forms of stone masonry construction are extremely vulnerable to earthquakes.

Stone and slate masonry

As evidenced in old houses, traditionally, the stone masonry is laid in mud mortar which contained large amount of clay and a "course" is made up of large sizes of stone blocks sandwich between many thin wafers (2 to 5 mm thick) slates arranged in layers. These thin wafers of slate are filled in the depressions of large stones to create an "even" course and finished outer (exterior) surfaces as shown in Fig. 1. The resulting stone masonry is different from typical random rubble (R/R) masonry. The wall thickness can vary from about 45 to 75 cm consisting of two wythes each of 20 to 30 cm thick separated by filler material. The filler material is loosely packed small stones and slates embedded in mud mortar. In well-constructed houses where quality of workmanship is good, throughstones are also used frequently to bind both wythes.

The damage to such masonry has been moderate to less depending on the quality of masonry and workmanship. Many layers of jointing material (mud mortar in most cases) provide a very large area for accommodating relative movements between masonry units (stone boulders and large number of thin slates) during the ground shaking and thus, dissipating energy through friction and material hysteresis. Furthermore, even weak mortar provides large lateral shear resistance through adhesion from large surface area available from many layers of jointing. However, its use has been declining because it is very time consuming to lay thin layers of slate. As a result, very few and thicker slates are being used with much larger pieces of stones and in some cases, the mud mortar is being replaced with weak cement-sand mortar. These masonry walls have experienced more damage, however, the use of cement-sand mortar has helped in many cases.

Random Rubble (R/R) stone masonry

In general, Random Rubble (R/R) stone masonry has no layers of thin slates to fill in the undulating contours of large stones to create even "courses." These walls are composed of two wythes with total wall thickness varying from 45 to 75 cm. Undressed stones are laid in mud mortar and plastered in cement-sand mortar to provide finished surface. Sometime exterior surfaces, especially of government buildings, are decorated in such a way that they give a false impression of Ashler stone masonry in which stone masonry units are dressed stone blocks laid in relatively thin layers of mortar (Fig. 2). This practice of R/R masonry is not "indigenous" to hill areas and seemed to have migrated from the plains during the colonial period. Most of government buildings, hospitals, schools, jails, etc., built during this period suffered heavy damage especially when the structure is old. The collapsed walls of Chamoli jail are one such example which left 7 dead and 11 seriously injured.

Clay Brick Masonry

The usage of burnt clay brick masonry is a recent phenomenon in hilly areas and appears to have been encouraged by Uttarkashi (1991) and Latur (1993) earthquakes where stone masonry walls have shown poor performance and were responsible for large number of deaths. Subsequent to these earthquakes, media , NGOs and engineering community have highlighted the vulnerability of stone masonry and propagated a preference for brick masonry. These brick masonry walls are generally laid in cement-sand mortar and often have been provided with lintel and roof bands (Fig. 3).

In general, clay brick units are much weak compared to stones and shear failure of brick masonry walls was noticed which developed familiar X or diagonal cracks. Almost all brick buildings which used RC slabs for roofs and floors; have beams and columns though not necessarily capable of developing frame action; and/or have lintel and roof bands; have performed satisfactorily, even when bricks walls themselves are weak.

Concrete Block Masonry

Besides clay bricks, concrete blocks are another variety of masonry units which are recently being used a replacement for stone blocks (Fig. 4). Many factors have contributed to its growing usage such as unavailability of new quarries, time consuming and labour intensive activity of laying stone and slate masonry, uneconomical due to large quantity of cement-sand mortar required per unit volume of masonry, transportation of clay bricks from the plains, and in general, poor performance of stone masonry.

Concrete blocks are made from cement, sand (fine stone powder, when sand is not available in high reaches) and coarse aggregate in various dimensions. Typical dimension being approximately 300 mm X 225 mm X 150 mm. Concrete blocks are laid in cement-sand mortar and are used in load bearing as well as infills in weak RC frame construction. Very minor damage to such masonry walls was observed.

Flexible Diaphragms

Pitched roofs have been the most popular choice as a roofing system for buildings. However, there are many variants of pitched roofs with varying degree of seismic performance. In rural areas and low cost houses, the roofs are either composed of wooden joists and planks or simple wooden trusses and rafters (Figs. 5 & 6). In general, very good quality of timber materials from trees like *Chir* and *Deodar* have been used. In some cases, branches from shrubs of *Ringal* and *Kail* are placed over rafters to support a layer of mud which is then covered by thin pieces of slates to provide a water-resistant cover (Fig. 7). In government buildings, wooden planks are placed on rafters to support the roofing material as shown in Fig. 8. Galvanized corrugated iron (GCI) sheets have also been used as a roofing material in many cheaply built school buildings.

These roofs are inherently weak in shear and can not tie the walls together even when they are properly connected to them. They are heavy when slates are used attracting large inertia forces and often slates were observed to be dislodged even when the roof supporting structure survived the shaking. Most of roof failures can be attributed to a combination of deficiencies such as loss of support of roof trusses and rafters due to failure of masonry walls and failure of roof truss itself due to failure of joints and/or members forming the truss or other roof supporting structure (Fig. 9).

Rigid Diaphragms

Flat reinforced concrete slabs are recent substitute for old fashioned pitched roofs and wooden flooring systems. These slabs are relatively rigid and have sufficient strength and stiffness. No failure of such slabs was noticed, however, often cracking in walls at the bottom level of slab was observed which is an indication of the relative displacement between the slab and the wall due to lack of connection between them. This lack of positive connection somewhat diminishes the beneficial effect of rigid diaphragms in enhancing the overall structural integrity.

Seismic Resistance Mechanism of Masonry Structures

The majority of masonry structures use the unreinforced masonry walls as bearing and enclosure walls. These masonry structures can be viewed as box-type structures in which the primary lateral resistance against the earthquake forces is provided by the membrane action of the diaphragms (floors and roofs) and bearing walls.

In the event of earthquakes, the ground motion is transmitted from the foundation to the end walls acting as in-plane structural walls whose response to the motions depends on height, wall stiffness and contributory masses from the floor diaphragms. At a given elevation these wall response motions act as input motions to the floor diaphragms, which resist the resulting inertia forces through their in-plane shear strength and integrity with the vertical elements. If the diaphragm is rigid, the response at all points along the floor will be equal to the end-wall response. However, if the diaphragm is flexible, as will often be the case for the existing masonry structures, the response may well be modified from the end-wall values. The response of the diaphragms in turn becomes the input motion for the URM walls in the out-of-plane direction. The out-of-plane walls resist the resulting inertia forces and maintain stability through the flexural action as observed in vertical beams. The above described behaviour of masonry structures and the flow of seismic energy is illustrated in Fig. 10.

Since the ground motion is modified by the actions of the end structural walls and of the diaphragms before acting as an input motion to the out-of-plane wall, the in-plane response of the masonry end walls directly affects the kinematic inputs to the walls and to the end of the diaphragms. Clearly, a rigid masonry wall would deliver larger motions to the diaphragms than flexible and ductile end walls, and the amount of amplification depends on the site soil conditions and on the aspect ratio of the wall. The interactions implied by this behavior are rather complex in nature and highly inter-dependent on various constituting elements. This gives rise to many different failure mechanisms for masonry structures as discussed in the following section.

Structural Deficiencies & Seismic Performance

There is little uncertainty in identifying common failure modes of majority of masonry structures in the earthquake affected region. As evidenced in many past earthquakes, the following are specific ways in which masonry structures have been found deficient in their earthquake-resistance mechanism. These vulnerabilities can be conveniently grouped into the following categories:

Out-of-plane wall failures

These are most commonly caused by the inadequate wall-diaphragm anchorage and by the out-of-plane bending resistance of the walls. The stone masonry walls which do not have enough throughstones to hold the both wythes together fail by splitting along the length of the wall jeopardizing its vertical load carrying capacity as seen in Fig. 11. Figure 12 shows another less damaging effect of this deficiency is a partial collapse of one of the wythes of the wall. Such out-of-plane failures arising from the dynamic instability of tall unsupported walls are also evident in collapse of gable end wall as shown in Fig. 12. This deficiency of stone masonry wall was more evident in R/R type masonry and was responsible for the majority of the observed damage in the earthquake affected areas.

In-plane wall failures

Walls subjected to in-plane inertia forces fail due to shear overstress and flexure instabilities. Shear failures are more brittle and catastrophic than flexure failures. Solid walls are in general are sufficiently strong to resist earthquake induced shear forces. However, many shear failures of R/R stone masonry walls was observed, which was primarily due to the fact that the walls could not maintain its integrity during the shaking. Moreover, masonry walls are weakened by openings for doors and windows (Fig. 13).

Diaphragm failures

Diaphragms fail due to inadequate shear strength and their poor connection to walls or other vertical elements. In the case of flexible diaphragms, deflections of diaphragms are so excessive that walls and partitions or cross walls are pushed out-of-plane. Flexible roofs, pitched, and double pitched roof have performed rather poorly (Fig. 14).

Configuration-induced failures

Configuration-induced failures arising from substantial plan and vertical irregularities have also been observed with masonry structures. The most common configuration problems are: overstress resulting from torsional effects, non-parallel vertical systems for corner buildings (Fig. 15), incompatible distortions at reentrant corners, accumulated damage in the first storey for houses on slopes as shown in Fig. 16.

Failures due to lack of structural integrity

It is very important that the all the building elements of masonry structures are tied together so that they can act together as one unit in resisting earthquake induced forces. If walls move inwards or outwards, diaphragms (roof and floor structure) will lose support and collapse. The lack of proper connection capable of withstanding compression and particularly tension at the following locations have been responsible for damages to number of buildings: between the perpendicular walls at corners for peripheral walls, between walls and cross-walls or return walls and between the walls and the diaphragms as shown in Fig. 17. The structures which have been provided with lintel and/or roof bands behaved satisfactorily and sustained expected minor damage in the areas of greater shaking. Figures 11 and 18 shows some of the examples of failures which are primarily caused by not tying building elements together and inferior construction.

Miscellaneous Buildings & other Structures

School and other community buildings

School and college buildings were one of the most affected by the earthquake. In many rural areas these were the buildings which had the poor construction and maintenance and consequently suffered moderate to heavy damage (Fig. 14). Hostel building for a Sanskrit college suffered extensive damage in Mandal (Fig. 12). The old Government Hospital buildings suffered heavy damage to its R/R masonry walls and fortunately they were unoccupied during the earthquake. However, those built recently and incorporated earthquake resistant features escaped with minor to no damage (Fig. 19). It is really fortunate that the earthquake struck in the middle of the night otherwise the injuries to children and loss of lives could have been substantial. It is very important that adherence to seismic codes for the construction of such community buildings must be made compulsory.

Many landmark buildings, such as temples, suffered no visible damage largely because of superior construction technique and remarkable workmanship. Most of temples which are over hundred years old are built using finely dressed stones. These stones pieces are kept in place in a course by steel hooks and mortar of lime and organic material with glue like properties. Frequent use of long stone slabs act like throughstones and provision of steel hooks provided mechanical anchorage and resistance against any lateral movement. The arrangement of roof slabs, provision of openings and other building dimensions were kept to enhance the overall structural integrity. Obviously these construction features required consumption of large amount of resources and could be afforded only for a few special projects. Figure 20 shows the landmark stone temple of Gopeshwar.

Roads and Bridges

The area has a large number of highway and pedestrian bridges over rivers, rivulets, and gorges. The highway bridges are made from a variety of materials (steel, reinforced concrete and stone masonry) and of various configuration and forms (trusses, T-beams and girders, arches). No damage to any of the highway bridges was noticed. Even older stone arch bridges have suffered no damage. Most of pedestrian bridges were of suspension types and no particular damage to the bridge structure or to the supporting pylons was noticed. However, in a particular instance near Chandrapuri some overstressing of old stone masonry pylons was noted. Fissures on roads were noticed at places which were primarily due to ground movement across unstable slopes.

Conclusions

The damage to built environment, economic loss and human casualties caused by moderate-size, shallow earthquakes increases proportionally with the growth of settlements and population. Conventional unreinforced masonry structures suffered the most damage near the epicentral region, and some of them were damaged beyond repair. Significant damage to residential , community and government buildings result from prevailing construction practices to meet requirements of a growing population in hilly areas, especially at low economic level. Buildings should not only meet the functional requirements of occupants but also the sound earthquake-resistant design and construction requirements.

Most of residential units in the affected area relied on load bearing masonry walls for seismic resistance. Much of the damage could be attributed to ageing, inferior constructions materials, inadequate support of the roof and roof trusses, poor wall-to-wall connections, poor detailing work, weak in-plane wall due to large openings, out-of-plane instability of walls, lack of integrity or robustness and asymmetric floor plans. These deficiencies can be easily removed or significantly reduced if the provisions of IS:4326-1993 (BIS 1993a) and IS:13828 -1993 (BIS 1993b) are followed for such constructions. The extent of damage would have been drastically reduced had modern earthquake-resistant design procedures and construction practices been followed, e.g., the provisions of the Indian seismic codes. However, some of the provisions of these IS codes need to be critically reviewed in the light of recent developments.

References

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2. BIS. (1993a). *IS:4326-1993 Earthquake Resistant Design and Construction of Buildings - Code of Practice*, Bureau of Indian Standards, New Delhi.
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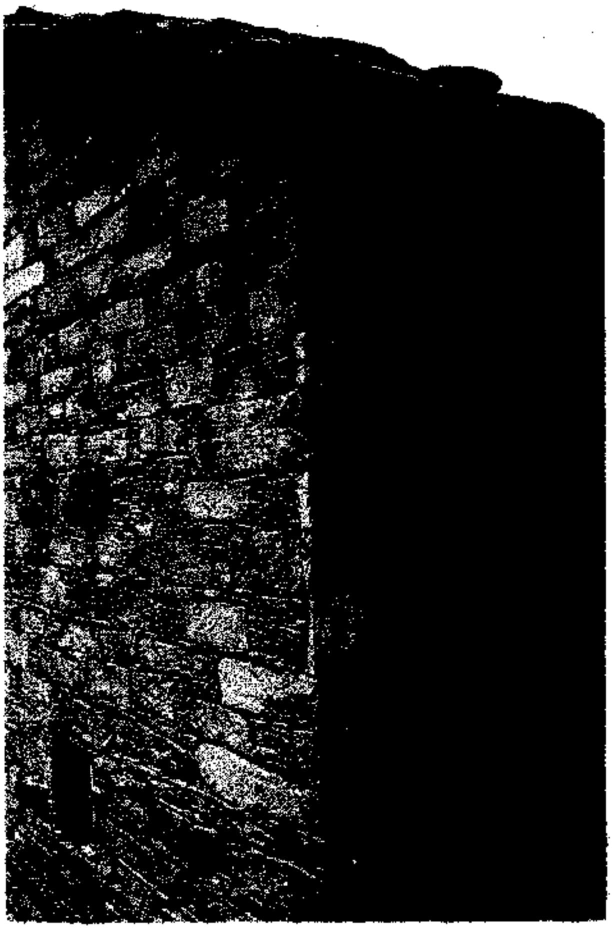


Fig. 1 Typical stone & slab masonry wall construction. Note slate for covering roof and small size openings in the gable wall.

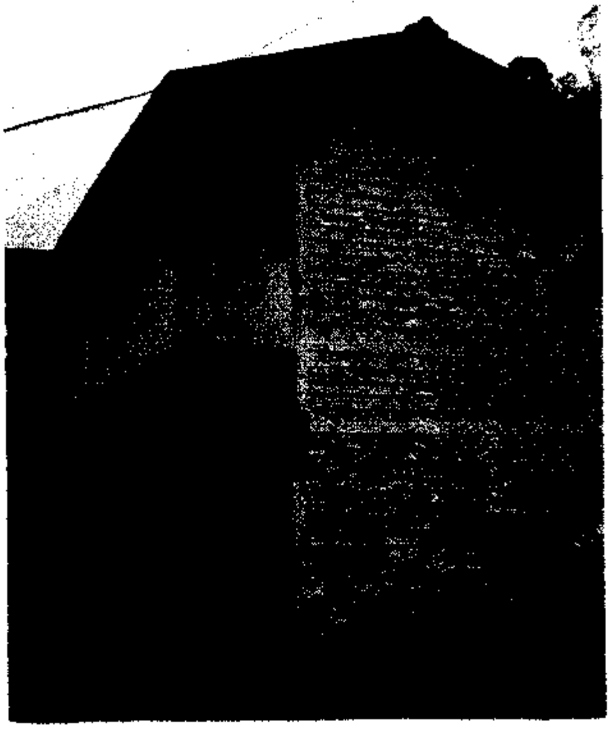


Fig. 2 In-plane shear failure of random rubble (r/r)stone masonry which is plastered and decorated to give an impression of dressed stone masonry.

Fig. 3 **Clay brick masonry house under construction. Note lintel band and gci sheets for placing the concrete slab.**

Fig. 4 **Second storey addition in concrete blocks where the ground storey is in r/r stone masonry.**

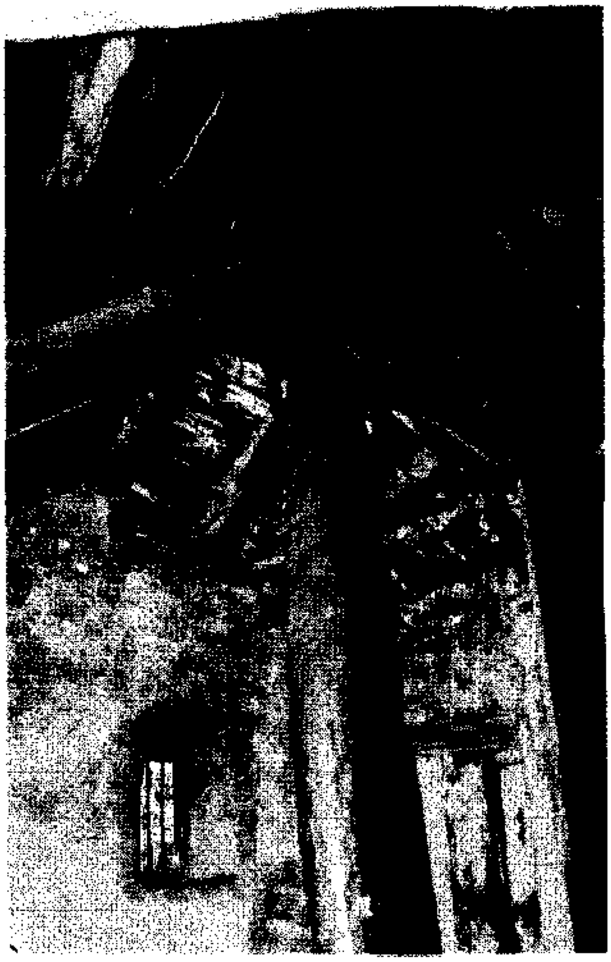


Fig. 5 Roof supporting structure in very old houses. Note the vertical member which supports the "ridge" rafter.

Fig. 6 Wooden truss, rafter and plank system widely used in government buildings. Exterior roofing cover is usually gci sheets. Also note the partial collapse of gable wall when inner wythe is dislodged.

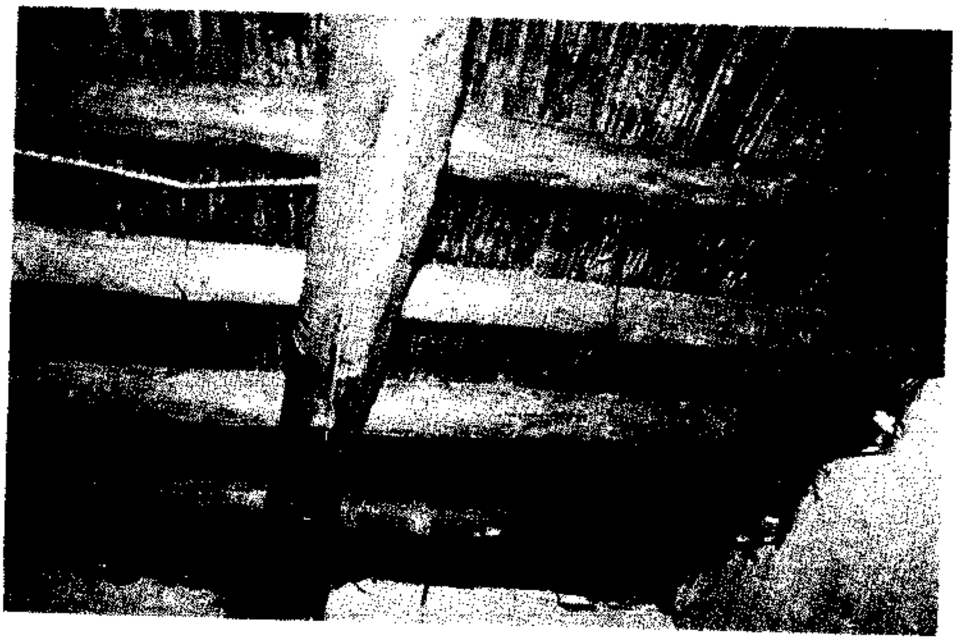


Fig. 7 Wooden logs and twigs of *rigal* and *kail* form the roof supporting structure.

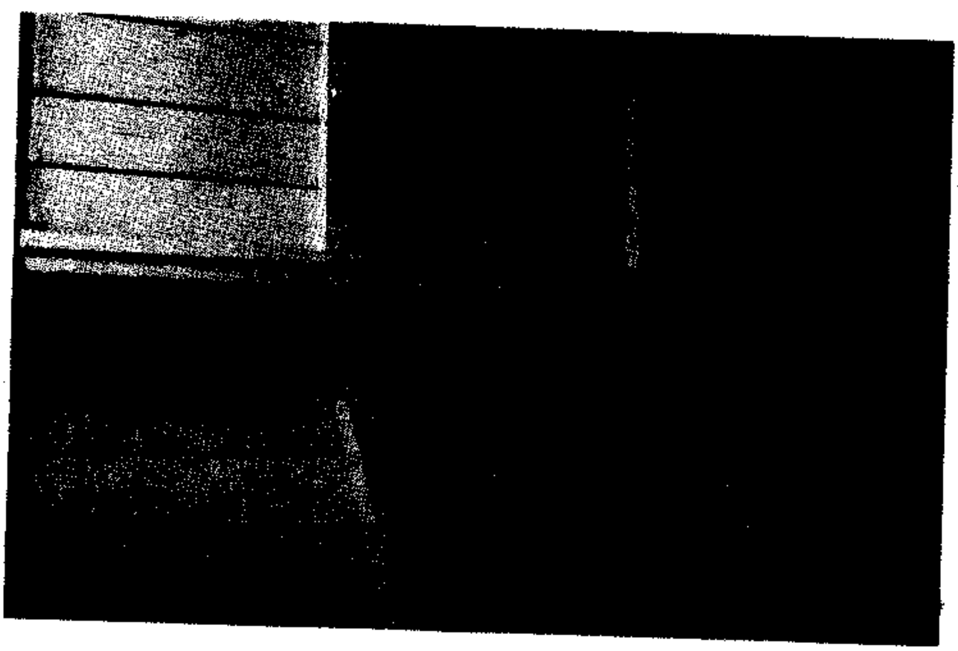


Fig.8 Wooden joist and plank system for roofs.

Fig. 9 Collapse of double pitched roof using wooden logs to make a supporting frame.

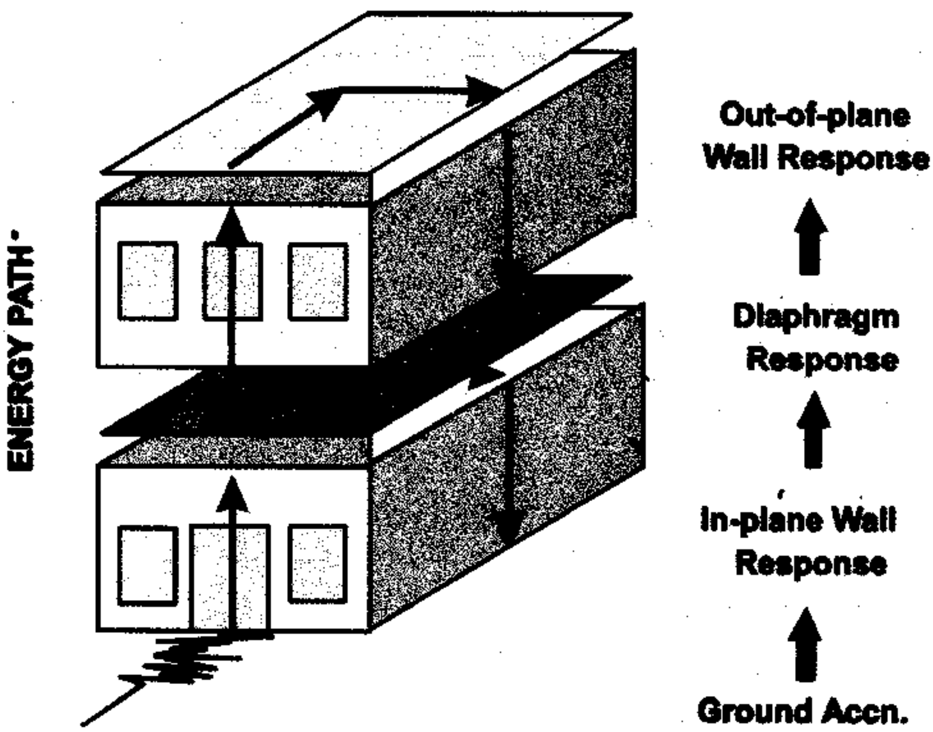


Fig. 10 Flow of seismic energy in various components of load bearing masonry structures.

Fig. 11 Out-of-plane collapse of r/r stone masonry walls.

Fig. 12 Collapse of end gable walls and cross walls (hostel building, mandal)

Fig. 13 Diagonal and x type shear cracks in newly built stone masonry house.

Fig. 14 Total collapse of roof due to out-of-plane failure of supporting wall and the roof supporting structure (school building, Bairagana).

Fig. 15 Non-parallel vertical system for a corner building (Lower Chamoli).

Fig. 16 Typical house on slope. Many such houses were damaged.

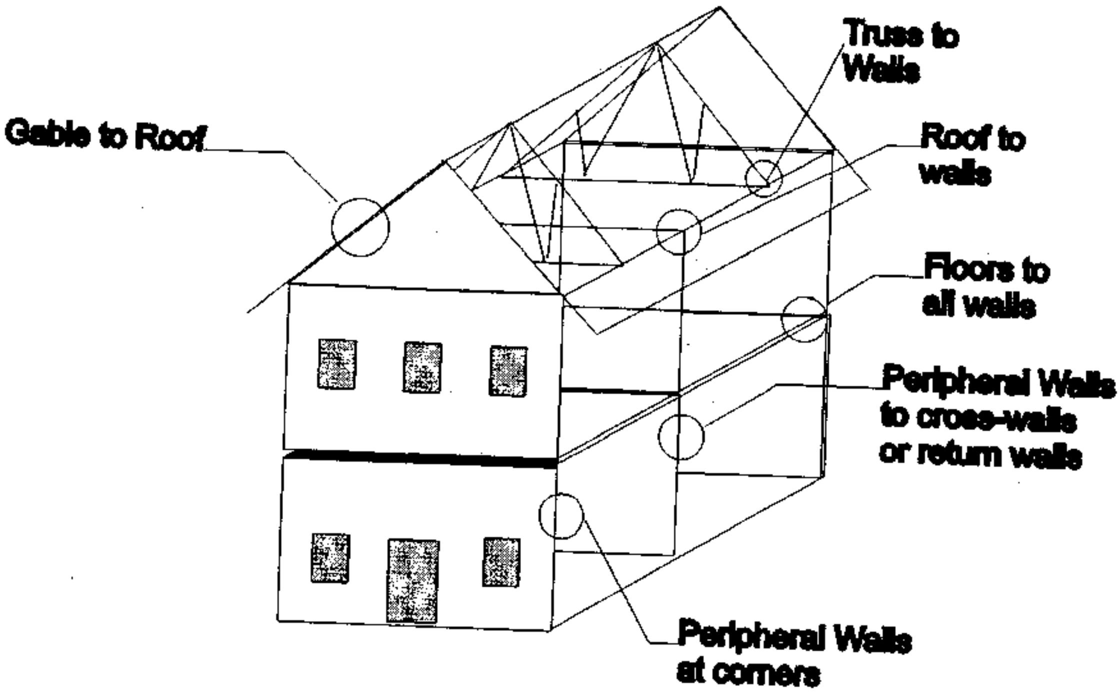


Fig. 17 **Locations inside a load bearing structure where tying of building elements is essential for a better seismic performance.**

Fig. 18 **Partial to total collapse of houses due to inferior construction and lack of structural integrity.**

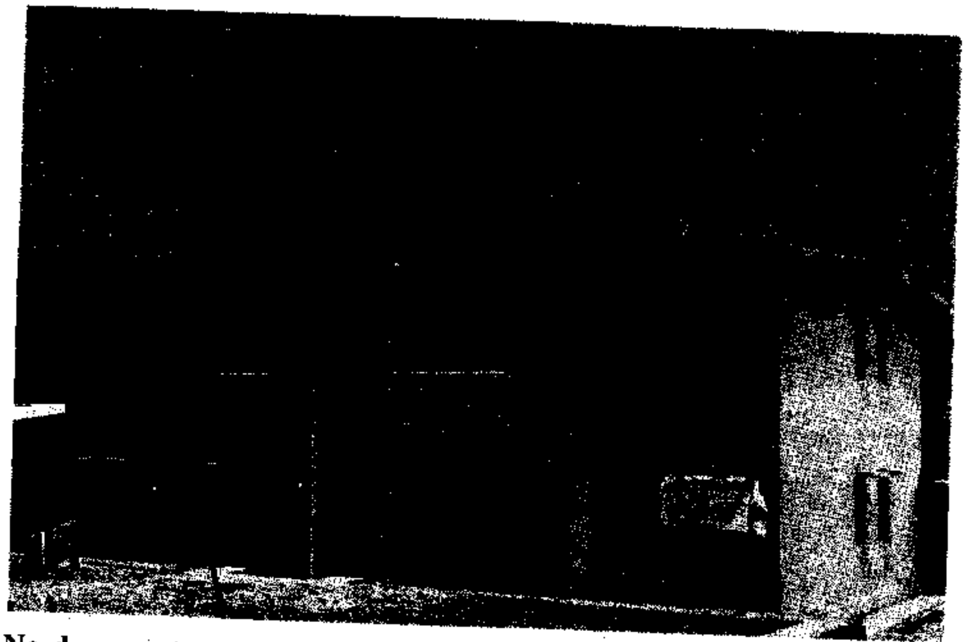


Fig. 19 **No damage to government hospital building in Mandal. Newly built structure uses earthquake resistant construction features.**

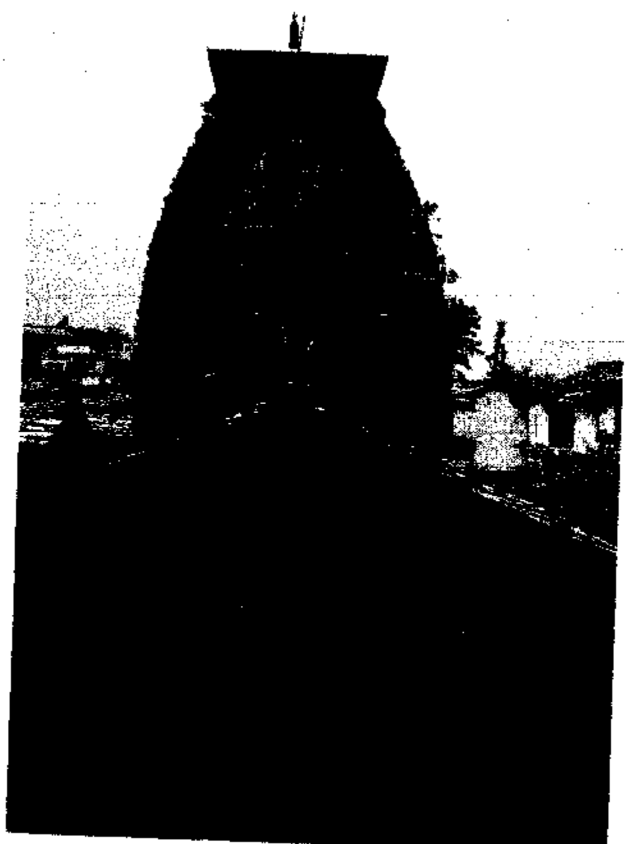


Fig. 20 Landmark temple of Gopeshwar.

Chapter 5

SCIENTIFIC ISSUES AND RELIEF OPERATIONS OPINIONS AND SUGGESTIONS

J. P. Narayan

In this chapter, highlights of the published newspaper reports on relief operations, damage assessment, scientific and technical issues as well as opinions of various individual officials with regard to Chamoli earthquake of March 29, 1999 are briefly presented. This earthquake got wide coverage in various national and local newspapers and electronic media. Newspapers concentrated on the damages to buildings/houses and properties; loss of human lives and live stocks; damages and problems related to lifelines like water supply, electric power, transportation and telecommunication; social and emergency response like debris removal, medical facility, relief aids, housing and shelter needs; geological deformations like landslides, fissures and natural springs; statements of scientists and engineers on various aspects like causes and prediction, earthquake resistant design and future planning; statements of government bodies, journalists and NGOs on the preparedness, rescue and relief operations and various other problems posed by rain, wild cats etc. The recent trend of increased public awareness about earthquakes has focussed considerable interest on the damage, rescue and relief operations, scientific and technical issues and future planning.

Relief and rescue operations

Relief operations were largely decentralized and relief committees were formed at the village levels headed by village pradhans. Six zones (Tehsil level), ten sectors (Block and Nagarpalika level headed by the ADM) and forty sub-sectors (Nyay Panchayat level headed by SDM) were formed. An earthquake information centre was set up at Gauchar, 60km away from Gopeshwar to receive and distribute relief materials as well as to help NGOs involved in relief operations so that they could directly approach the villages instead of approaching district headquarters (The Statesman, April 5, 1999). The Union Cabinet declared a package of assistance from Prime Minister's relief fund for the severely damaged earthquake areas (Exhibit 1). Emergency service activity and restoration to the normal condition immediately following the earthquake was very difficult due to the lack of approach to the remote areas and blocking of roads caused by the landslides. The role of newspapers, government organisations, Army and NGOs is described as follows.

Role of newspapers

Newspapers played a vital role in relief operations by creating earthquake awareness in public and motivating various NGOs for the relief and rescue operations. On the very next day, most of the newspapers published the information regarding the casualties in various villages and towns and identified the severely affected villages/towns, so that government agencies and the various NGOs could directly approach the relevant places. In addition to this, newspapers provided information for the scientists e.g. the extent of felt area and the least and the most damaged villages/towns (Exhibit 2). The newspapers also reported the areas which were blocked due to the heavy landslides and the far flung areas, so that various NGOs and government agencies can reach these places by appropriate means.

Mr. S.M.A. Kazmi of Indian Express noted that while the victims living on the road side were flooded with relief supplies people living in the remote/interior mountainous areas did not get any help (The Indian Express, April 5, 1999). The newspapers also reported the statement of some victims, "The 'sher' (wild cat) is on the prowl and we do not know how long we will survive in this torn tent", published under the heading "After the tremors fear of wild cat", to warn the residents of the area with the possible attack of wild cats (The Hindu, April 2, 1999).

Role of Government Organisations

Uttar Pradesh Chief Secretary, Dr. Yogendra Narain told press-person that Chief Medical Officer of Chamoli had dispatched five medical teams to the rural areas to assist rescue and relief operations. Thirteen other teams were dispatched from Dehradun, Rudraprayag, Saharanpur, Hardoi, Narendra Nagar and Srinagar. A State Government helicopter was sanctioned for Gopeshwar City to airlift the injured people. Ambulances were placed at strategic points on the highway so that the injured could be taken to hospital immediately (The Hindu, March 30, 1999).

Mr. Kalyan Singh, the then Chief Minister of Uttar Pradesh, constituted an all party committee to supervise the relief operations in the quake affected areas (The Indian Express, April 6, 1999).

Role of NGOs

A number of NGOs and social organisations were involved in the rescue and relief operations. Oil and Natural Gas Corporation Ltd. (ONGC) distributed medicines to the sick and the injured people in the affected areas (Panjab Kesari; April 7, 1999). Red Cross Society (RCS) got involved in relief works like survey and preparing relief cards to the victims of the villages (The Pioneer, April 4, 1999). Bharat Heavy Electrical Ltd. (BHEL) sent a team of doctors in the guidance of Dr. Ghosiya to the affected areas (Amar Ujala; April 3, 1999).

Role of Armed forces

Personnel from the Indian Army, Indian Tibetan Border Police (ITBP), General Reserve Engineers Force (GREF), Secret Service Bureau (SSB) and Border Road Organisation (BRO) were involved in relief works like removal of debris of landslides blocking the roads, water supply, surveying and preparing relief cards to the victims in the villages. Army Jawans were the first to pull out the wailing men, women and children from under the debris and even performed the task of assessment of loss of human lives and cattle and damage to houses and property. Exhibit 3 highlights the role of Army and their excellent performance during relief operations. Army reached several remote areas like Mandal valley which had so far remained inaccessible to government officials involved in the relief work. Indian Air Force (IAF) helicopters were inducted for carrying relief materials consisting mainly of rations and clothings to the quake hit regions. IAF had also set up a radio link at Joshimath for continuous up-gradation and co-ordination of the relief operations and to assess the extent of damage in the area (The Pioneer, April 4, 1999). ITBP made a makeshift hospital to admit and treat the injured people (The Pioneer, April 1, 1999).

Damage assessment

A number of government agencies, scientists and engineers from different institutions got involved in the damage assessment. A six-member committee comprising of U.P. Housing Secretary and a Professor of Department of Earthquake Engineering, University of Roorkee, Roorkee was set up by Union Urban Ministry to examine all the issues related to damage and make recommendations for the measures to be taken (Exhibit 4). Housing and Urban Development Corporation (HUDCO) sent a team to Chamoli and Rudraprayag to assess the damage to the housing stocks and evolve a plan of action for re-construction, repair and retrofitting of the houses (The Hindu, March 31, 1999). Dr. S. K. Srivastava, Joint Director, IMD, New Delhi told The Hindustan Times that the damage was less due to deeper focal depth (about 30km) of the earthquake and life loss was also less due to thinner population density (The Hindustan Times, March 30, 1999).

Scientific and Technical Issues

Prof. Avadh Ram, Banaras Hindu University and Dr. V.C. Thakur, Director, Wadia Institute of Himalayan Geology estimated a shallow focal depth of the earthquake (Amar Ujala, March, 30 and The Hindustan Times, March 30, 1999). A geologist of Uttar Pradesh Directorate of Geology and Mining said that all their report were treated as 'formality' and never taken seriously (The Times of India, April 3, 1999). According to Hindustan "Lesser production of eggs was reported by the poultry forms during 3-4 days before the mainshock and this effect was marked just before even every major aftershocks", (Hindustan, March 31, 1999). The statements and the views of the some scientists and engineers on the earthquake prediction, their causes and quake resistant design published in the newspapers are given below.

Prediction

According to Prof. Ramesh Chander, Department of Earth Sciences, University of Roorkee the exact earthquake prediction is only possible if we have 200-250 years of seismic data. Further, Prof. A.S. Arya, Emeritus Professor, Department of Earthquake Engineering, University of Roorkee told the newsman, "It will take another 50 years for exact earthquake prediction" (Amar Ujala, April 1, 1999). Dr. R.N. Iyengar, Director, Central Building Research Institute (CBRI), Roorkee told that if the help of satellites is taken in collecting the data regarding the earthquake then earthquake prediction may be possible (Amar Ujala; April 1, 1999). According to Dr. J.G. Negi, Emeritus Scientist, National Geophysical Research Institute (NGRI), Hyderabad, Joshimath-Uttarkashi region is emerging as a zone of significant new tectonic movement (The Hindustan Times, March 30, 1999).

Bigger shock expected

Dr. J.G. Negi, NGRI, Hyderabad told to the Indian Express newsman, " It is going to be a big bang-8 plus",. Further, he added, "The Joshimath-Uttarkashi region has been unusually quiet far over 50 years after a series of powerful quakes between 1897 and 1934". Dr. B. K. Rastogi, Deputy Director, NGRI, Hyderabad, Dr. S.K. Dikshit, Deputy Director, India Meteorological Department (IMD), New Delhi also reportedly mentioned that a big quake might hit the Himalayan belt any time (The Indian Express, March 31,1999).

Prof. S.P. Sinha and Dr. Ajay Nathani, Department of Geology, Garhwal University told Nav Bharat Times that these aftershocks were good for the region since most of the accumulated energy would be released and no big quake will occur in near future (Nav Bharat Times, April 1, 1999).

Aftershocks

Dr. H.N. Srivastava, Emeritus Scientist, IMD, New Delhi expressed that " An earthquake of this magnitude (6.8 on Richter scale) is followed by aftershocks which may continue for two months and people should be alert", (The Hindustan Times, March 30, 1999).

Landslides

According to Mr. Chandi Prasad Bhatt, noted environmentalist and Ramon Magsasay Award winner, "Water seepage from wide cracks could trigger heavy landslides, soil erosion and collapse of entire hills any time within one to ten years of the quake" (The Hindustan Times, April 2, 1999). Mr. Bhatt recalled that similar cracks caused by the Uttarkashi earthquake (1991) around Burwa and Bhanti village had led to massive landslides that swept away some villages in the Rudraprayag district. Prof. A.K. Pachauri, Dr. Isreal and Dr. (Mrs.) I. Sarkar of Department of Earthsciences, University of Roorkee warned of increased seismic activity in the Garhwal Himalayas in near future and landslides following heavy rains (The Indian Express, April 6, 1999).

Earthquake cause

Late Dr. Jai Krishna, internationally renowned expert, Emeritus Professor and former Vice Chancellor University of Roorkee expressed that earthquake occur due to disturbances in the interior of the earth but nothing can be said about the nature of such disturbances. However, if buildings are constructed according to specified standards then loss of life and property can be reduced and this depends on the economic condition of the people in the area (Exhibit 5).

Earthquake resistant design

According to Dr. A. S. Arya, Emeritus Professor, University of Roorkee "An additional expenditure of a mere 6% during the construction can make the building quake resistant", (The Hindustan Times; April 2, 1999). Dr. Durgesh C. Rai, Structural Engineer, Department of Earthquake Engineering, University of Roorkee suggested that houses in the affected region should be constructed on the lines of that in the post – 1993 quake in Latur (The Times of India, April 4, 1999). Housing and Urban

Development Corporation (HUDCO) adopted two villages namely, Ghighran village of Chamoli district and Kyunja village of Rudraprayag district to develop model houses (The Statesman, April 4, 1999).

Recommendations and suggestions made by various organisations and individuals for future actions

Recommendations, suggestions and statements of the various government bodies, scientists and engineers of various institutions and NGOs were made which related to dense seismic monitoring of the rocked area, earthquake resistant design and geophysical and geological survey of the affected region. These are given in the following sections.

Government of Uttar Pradesh

Mr. Kalyan Singh, the then Chief Minister of Uttar Pradesh requested the centre to conduct a comprehensive scientific survey of Chamoli and Rudraprayag districts. "This survey will help in taking measures to deal with such calamities in future", Mr. Kalyan Singh told press person after surveying the quake hit areas (The Hindu, March 31, 1999). Mr. Kalyan Singh also indicated that State Government was planning to ask the centre to declare the earthquake in the U.P. hills as a "National Disaster", as given in the Exhibit 6. Dr. Yogendra Narain, Chief Secretary, U.P. Government told Amar Ujala newsman that a team of Geoscientists will survey the hill areas to find out the causes of the earthquake and landslides. The team will also find out how to reduce the damage caused by quakes and landslides (Amar Ujala, April 3, 1999).

Scientists and Engineers

Dr. Janardhan Negi, Emeritus Scientist, NGRI, Hyderabad told newsman that despite North India sitting on a powder keg with a small fuse, the government was not showing adequate concern. Dr. Negi said " We had told the Government and Department of Science and Technology (DST), New Delhi that the area needed close monitoring through a string of seismological stations to detect any unusual movement". According to him Nepal and China had set up quake research institutes and put an earthquake policy in place while India was still waiting for a bigger catastrophe to strike. Dr. Negi has been recommending intensive seismic monitoring in the region, as stresses are building up and there has been no major quake since 1934. But no action was taken on the recommendation he added (The Indian Express, March 31, 1999). Dr. V.C. Thakur, Director, Wadia Institute of Himalayan Geology (WIGH) told The Hindustan Times during an exclusive interview that earthquake can neither be prevented nor predicted and therefore we should learn to live with this phenomenon. He advocated creating awareness and not panics among the people. People living in the earthquake prone areas should take adequate care in constructing their houses (The Hindustan Times, April 9, 1999).

Prof. S. Basu, the then Head of Department of Earthquake Engineering, University of Roorkee said that it would be more prudent to invest a small sum on disaster mitigation through better preparedness among the people rather than spending huge sum on post –disaster rehabilitation programs. Further, he added that his department had done pioneering work on improving the earthquake resistance of traditional houses of the hill regions and the technology was available at nominal cost

(The Hindu, April 1, 1999). According to Dr. Mohan Panwar, an Ecologist & Professor at Garhwal University "If the administration is serious enough to prevent likely tragedies, they have to build fresh houses and erect embankments at strategic points over the terraces on the hills to curb soil erosion", (The Hindustan Times, April 2, 1999).

NGOs

Ramon Magsasay award winner Mr. Chandi Prasad Bhatt advocated age-old "Jod-tod" method a traditional hill architecture for quake resistant designs. Further, he recommended single story buildings in the area (The Pioneer, April 3, 1999). Dr. Subhash Bhatt, NSS Officer told the newsman that the emission of Radon and carbon-di-oxide from the fissure had contaminated the ground water and air whose effects were visible in the form of people suffering from vomiting, loose motion, stomach-ache and eye problems and recommended detailed geological and geophysical survey of the affected area (Panjab Kesari; April 7, 1999).

References:

1. Amar Ujala; March 30 & April 1, 3, 1999.
2. Hindustan; March 31 and April 2, 1999.
3. Panjab Kesari; April 7, 1999.
4. The Hindu; March 30, 31 & April 1, 2, 1999.
5. The Hindustan Times; March 30, & April 2, 3, 9, 1999.
6. The Indian Express; March 31 & April 5, 6, 1999.
7. The Nav Bharat Times; April 1, 1999.
8. The Pioneer; April 1, 2, 3, 4, 1999.
9. The Statesman; April 4, 5, 1999.
10. The Telegraph; March 30, 1999.
11. The Times of India; April 3, 4, 7, 10, 1999.

Centre announces quake relief package

By Our Special Correspondent

NEW DELHI, March 30.

The Union Cabinet today decided on a package of assistance from the Prime Minister's Relief Fund for those affected in the devastating earthquake that struck the Garhwal region of Uttar Pradesh on Sunday night.

Under the package, the next of kin of the dead would get a compensation of Rs. 1 lakh if the dead was the bread-winner of the family, and Rs. 50,000 in case he/she was not. The package also includes an assistance of Rs. 10,000 for the grievously injured.

The Information and Broadcasting Minister, Mr. Pramod Mahajan, said the relief would be in addition to that announced by the Uttar Pradesh Government.

As regards the Central assistance to Uttar Pradesh, he said a decision would be taken after the team consisting of the Planning Commission Deputy Chairman, Mr. K. C. Pant, and the Union Agriculture Minister, Mr. Sompal, leaving for the affected region tomorrow, presents its report.

The package would be finetuned based on the report of a Central experts team that is also leaving for the affected areas tomorrow. All possible assistance would be rendered to Uttar Pradesh to restore normalcy.

The Cabinet, which met here this morning, also placed on record its anguish over the havoc and condoled the loss of life and property.

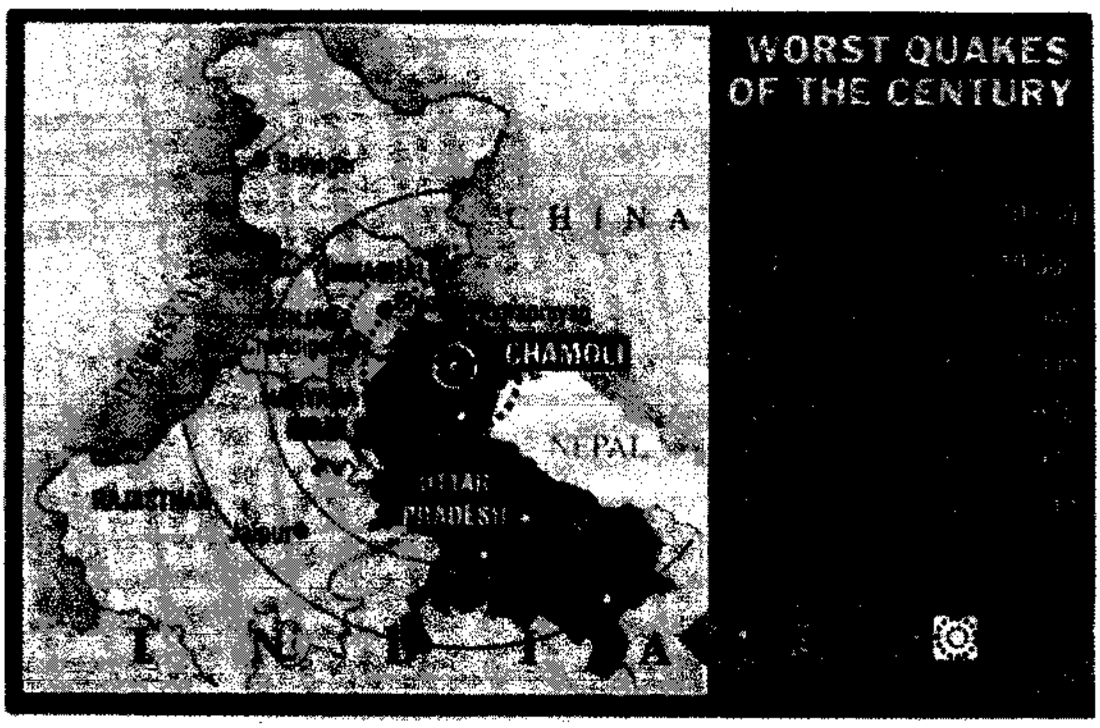
Meanwhile, a five-member team of seismic experts from the Indian Meteorology Department has left for the affected zone for monitoring the seismic activities there. The team, equipped with sophisticated equipment to detect even the minutest of tremors, would be there till the situation became normal, said Dr. S. K. Srivastava, Additional Director General in charge of seismology, at the IMD.

He also said that after-shocks with magnitudes averaging 3 on the Richter scale were continuing. It was quite normal. They might go on for some more time, he said.

The Housing and Urban Development Corporation has also sent a team to Chamoli and Rudraprayag to assess the damages to the housing stock and evolve a plan of action for re-construction, repair, renewal and retrofitting the houses, besides rehabilitation of the water supply and other utilities.

The Chairman and Managing Director of the HUDCO, Mr. V. Suresh, said the public sector techno-financial agency would do its best to back-up the State Government's efforts to rehabilitate the victims through financial assistance and technology transfer support for providing earthquake-resistant construction.

(Exbt.1) Union Cabinet earthquake relief package (The Hindu, March 31, 1999).



(Exbt.2) Areas jolted by the earthquake (The Telegraph, March 30, 1999)

Men in uniform offer succour to quake-hit people

GOPESHWAR: Though trained to defend national boundaries under adverse circumstances, the Army once again proved its worth in bringing succour to the people as a deadly quake hit the ecologically fragile Himalayan region in Chamoli and Rudraprayag districts.

The men in uniform were first to pull out the wailing men, women and children from under the debris, limiting the toll to the minimum possible.

Army jawans in Chamoli district even performed the task like assessing the loss of human lives and cattle and damage to houses and property in the first phase, a prerogative of civil administration.

Lauded for their role in speedy relief to the quake-affected people, the jawans were much ahead of their civilian counterparts in the post-disaster operations.

Whether it was survey of the quake-hit far-flung villages, many of them without roads, or providing immediate relief in the form of food and temporary shelter, the toughly built men were seen working overtime while, agitated survivors alleged, the administration found it difficult to handle the chaos created by the devastating tremor.

With the civil administration struggling to extend relief work, the people of the worst-affected villages in the twin districts said they had pinned their hopes on the Army.

The administration, which initially tried to cope with the situation on its own, had to finally seek active participation of Army and para-military forces even in assessing the damage.

At one point of time, quake-affected people, dissatisfied with the slow relief operations of public works department (PWD) and other government agencies, demanded handing over the operations from civil administration to the Army.

Difference in the style of working of civilians and men in uniform was clearly visible at most of the affected spots as Army jawans braved the adverse climatic conditions and treacherous mountain terrains, scaling inaccessible areas which were cut off by landslips.

When severe water crisis plagued Gopeshwar following the quake, Armymen swung into action and installed a water pump in Dewar village, four km from here, with a capacity to pump out 2,000 litres every 10 minutes, bringing relief to the locals.

Apart from supplying 5 to 6 lakh litres water to Gopeshwar and nearby areas, the Engineering Corps of Garhwal Scouts and Rajput Regiment worked day and night and helped restore full water supply in the area in just six days.

Fighting against all odds, they cleared roads, replaced damaged pipelines and helped restore communication networks at a commendable speed. PTI

(Exbt.3) Role of army and government agencies in the relief operations (The Times of India, April 7, 1999).

Panel to assess damage in quake-hit areas

The Times of India News Service

NEW DELHI: A high-powered six-member committee has been asked by the Union urban ministry to prepare a reconstruction and repair plan for earthquake-hit Chamoli and Rudraprayag districts of Uttar Pradesh.

V Suresh, chairman of Housing and Urban Development Corporation (HUDCO) will chair it.

Uttar Pradesh's housing secretary and a professor of earthquake engineering from Roorkee University are members on the panel which will examine all the issues relating to the damage in the region and recommend follow-up measures.

(Exbt.4) Panel for damage assessment and to make recommendations (The Times of India, April 10, 1999).

'पृथ्वी की आतंरिक हलचल के कारण भूकंप आते हैं'

रुड़की, 1 अप्रैल (ह. सं.)। रुड़की विश्वविद्यालय के पूर्व कुलपति एवं वरिष्ठ भूकम्प वैज्ञानिक डा. जय कृष्णा का कहना है कि पृथ्वी की आन्तरिक हलचल के कारण भूकम्प आते है। उन्होंने कहा कि यदि मजबूती से पक्के मकान बनाए जाएं तो जानमाल के नुकसान को बहुत हद तक सीमित किया जा सकता है।

जाने-माने भूकम्प वैज्ञानिक डा. कृष्णा ने एक मुलाकात के दौरान बताया कि इतना तो तय है कि पृथ्वी की आन्तरिक हलचलों के कारण भूकम्प आते . लेकिन आन्तरिक हलचलें किस तरह की है, इस संबंध में कुछ नहीं कहा जा सकता। इसके अलावा उन्होंने कहा कि इस भूकम्प का केन्द्र चमोली में था लेकिन इसकी हलचल दिल्ली तक महसूस की गई। भूकम्प आने से पूर्व कोई भविष्यवाणी नहीं की जा सकती। उन्होंने कहा कि यदि निर्धारित मापदंडों के मुताबिक पक्के मकान बनाए जाएं तो नुकसान को कम किया जा सकता है और यह लोगों की आर्थिक स्थिति पर निर्भर करता है।

(Exbt.5) Earthquake causes (Hindustan, April 2, 1999).

Declare quake a national disaster, says Kalyan

Pioneer News Service
Lucknow

EVEN WHILE the state government is planning to ask the Centre to declare the earthquake in the UP hills as a "national disaster", it placed under suspension Garhwal Division Commissioner BM Vohra, on charges of laxity in rescue and relief operations.

The government has also exempted the recovery of land revenue and irrigation charges in the earthquake-affected regions.

Chief Minister Kalyan Singh made these announcements in the Vidhan Sabha on Wednesday. Moreover, MLAs of all political parties in the House decided to donate their one month's salary to the Chief Minister's quake relief fund.

The Chief Minister asked all members to visit the quake-affected region to monitor distribution of relief works and said no irregularities in relief distribution would be tolerated.

Hitting out at the Opposition, he said it was unfortunate that they had stated that natural disasters occured whenever he became the Chief Minister. He questioned, "Do you think I invite natural disasters?" He told the House that the government was fully aware and sensitive to the damage caused by the earthquake and said rescue and relief operations would be started immediately.

Denying all speculations, the Chief Minister said the quake had no impact on the Tehri Dam project. He announced the setting up of a Chief Minister's relief fund for the quake victims.

Minister for Uttranchal Development Ramesh Pokhariyal said, at least 500 persons were saved by the timely rescue and relief operations. He said the quake should not be made into a political issue but everyone should cooperate in assisting relief work.

Earlier, Reoti Raman Singh, Ambrish Kumar, Munna Singh Chauhan, Ram Autar Shakhya (Samajwadi Party), Harvansh Kapoor (BJP), Pramod Tiwari, Jagdambika Pal (Congress), Swami Prasad Maurya (Bahujan Samaj Party), Subhash Chandra Srivastava (Janata Dal) and Samarpal Singh Singh (Lok Dal) demanded a long term plan to tackle natural disasters.

The Chief Minister, in his statement to the House, said three districts of Garhwal division, namely Chamoli, Rudraprayag and Tehri were severely affected by the earthquake which took a havy toll on human lives and caused extensive damages to property.

Mr Singh had visited the places on Tuesday along with a team of senior officers and had personally supervised the relief and rehabilitation works in the quake-hit areas.

(Exbt.6) Long term planning demand to tackle natural disaster
(The Pioneer, April 2, 1999).