

## **Chamoli (Himalaya, India) Earthquake of 29 March 1999**

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### ***Introduction***

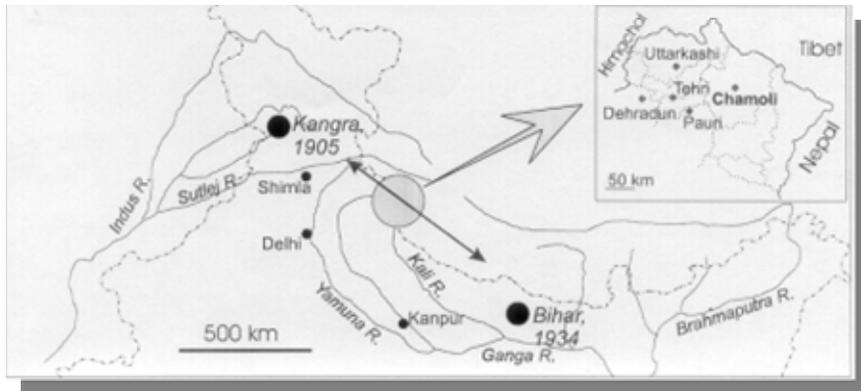
The Chamoli earthquake of 29 March 1999 in northern India is yet another important event from the viewpoint of Himalayan seismotectonics and seismic resistance of non-engineered constructions. The earthquake occurred in a part of the Central Himalaya, which is highly prone to earthquakes and has been placed in the highest seismic zone (zone V) of India. There has been a bitter controversy during the recent years regarding the seismic safety of a 260-m-high rock-fill dam under construction at Tehri, about 80 km west of the epicenter. Fortunately, there are no major cities in the meizoseismal region and the population density is the second lowest in the state. The earthquake caused death of about 100 persons and injured hundreds more. Maximum MSK intensity was up to VIII at a few locations.

Two separate groups carried out the post-earthquake investigation. A five-member group conducted a nine-day survey of the worst-affected areas, a week after the quake. This group consisted of Sudhir K. Jain (EERI 1987), C.V.R.Murty (EERI 1995) and Jaswant N. Arlekar (all three of the Department of Civil Engineering at the Indian Institute of Technology Kanpur), and C.P.Rajendran and Kusala Rajendran (scientists at the Center for Earth Science Studies, Trivandrum). Ravi Sinha (EERI 1996) of the Department of Civil Engineering at the Indian Institute of Technology Bombay also conducted a six-day survey of the meizoseismal area four days after the event. The Earthquake Engineering Research Institute, USA, sponsored the visits of the above persons as part of the *Learning From Earthquakes* project funded by the National Science Foundation, USA.

This report summarizes the observations made by the team on the seismotectonic setting of the earthquake, behaviour of structures, and the emergency response.

### *General Aspects of the Earthquake*

The earthquake occurred at 00:35:13.59 hours (local time) near the town of Chamoli in the state of Uttar Pradesh in northern India (*Figure 1*). The earthquake magnitude is mb 6.3, MS 6.6 as per USGS, and it is mb 6.8, MS 6.5 as per India Meteorological Department (IMD). The preliminary location of epicenters by different agencies is somewhat inconsistent; 30°49.2'N, 79°28.8'E as per USGS, and 30°17.82'N, 79°33.84'E as per IMD (*Figure 2*). Distances referred in this report are with respect to the USGS location. Location of aftershocks recorded and the damage pattern suggest that the zone of activity may be close to Chamoli town; this region also showed a maximum intensity of VIII on MSK scale. USGS estimate of the focal depth is 12 km.



*Figure 1:* Sketch of northern India showing locations of two great earthquakes, Kangra (1905) and Bihar (1934). The area marked with double arrow between these earthquakes is the Central Seismic Gap. Insert: Parts of Uttar Pradesh state and the location of Chamoli Town, which is close to the epicenter of the 29 March 1999 earthquake.

The quake was felt at far-off places such as Kanpur (440 km south-east from the epicenter), Shimla (220 km north-west) and Delhi (280 km south-west). Maximum death and damage occurred in the district of Chamoli where about 63 persons died and over 200 injured; about 2,595 houses collapsed and about 10,861 houses were partially damaged. In all, about 1,256 villages were affected. A few buildings at the far away mega-city of Delhi sustained non-structural damages. No instances of liquefaction were reported. Longitudinal cracks in the ground were seen in some locations in the affected area.

The earthquake was followed by intense aftershock activity; this included at least 3 events of  $M > 5$ . Most of the aftershocks are located to the east of Chamoli (Figure 2). The fault-plane solution obtained from the USGS (Figure 3, insert) indicates a pure thrust mechanism with two nodal planes striking at  $282^\circ$  and  $97^\circ$ . The first one is preferred because it conforms to the field observations.

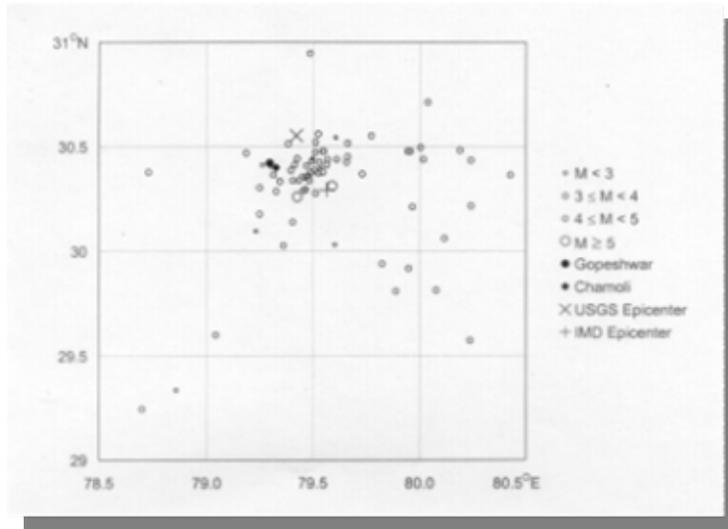


Figure 2: Aftershock locations of the 1999 Chamoli earthquake recorded up to 8 April 1999 as per data from India Meteorological Department [IMD]

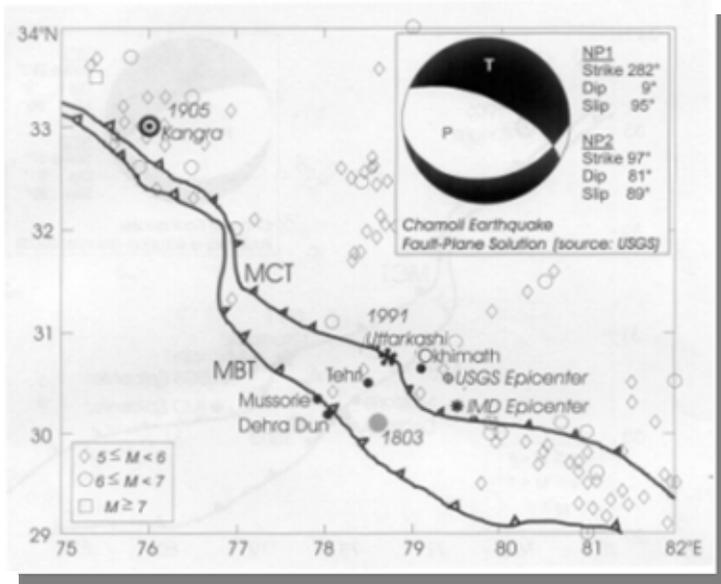


Figure 3: Spatial pattern of seismicity in Garhwal Himalaya during 1684-1985 with respect to two of the major thrusts MCT and MBT [Khattri et al., 1989, Proc. Indian Acad. Sci. (Earth. Planet. Sci.), 91-109]. The subsets

MCT I, II, III are not marked. Shaded dot indicates the location where maximum intensity (VIII - IX on MM scale) was observed during the 1803 earthquake. *Insert:* Fault-plane solution of the main shock at Chamoli.

### *Geologic and Tectonic Setting*

The Himalayan mountain range, an outcome of the compressional processes ensued by the India-Asia collision (70-40 Ma), has been undergoing extensive crustal shortening along the entire 2400-km-long northern edge of the Indian plate. A series of thrust planes is known to have formed as a result of these processes. Three principal thrust planes in the Himalayan region are the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT). Two of the major thrusts and the regional seismicity are shown in *Figure* 3.

The MCT is believed to have developed by an intra-crustal thrust that brought up the mid-crustal level rocks of the Higher Himalayan Crystallines to the Lesser Himalaya. Tectonically, it represents a ductile shear zone at depth, comprising a duplex zone with three distinct sub-thrusts: MCT I, MCT II and MCT III from south to north. Of these, MCT-I, the southernmost and the youngest, appears to be seismically more active. Several damaging earthquakes have occurred along these thrust faults, and there are continuing debates on the current seismogenic potential of these fault systems. The M6.5 Uttarkashi earthquake of 1991, centered about 70 km north-west of Chamoli town, is considered to be associated with this fault. The Chamoli earthquake also appears to be associated with the same fault. Observations of recent deformation in the epicentral region also support this inference.

#### *An Active Fold?*

The Lesser Himalayan sequence lying between the MCT and the MBT shows stacking of various groups of rocks characterized by south-vergent thrusts, which were later folded into major scale synforms and antiforms. The geological maps of the area indicate presence of anticlinal structure very close to Chamoli. During the post-earthquake field investigation, some signatures of recent deformation, associated with this anticline, were observed. A sharp contact of MCT-I with recent/sub-recent deposits is identified near Chamoli on the southern flanks of the anticline along the Alaknanda river. Thick deposits of *colluvium* (boulders and pebbles intercalated with coarse sand) occur at the foot of the steeper limb of the fold. The colluvium may have been remobilized on an incipient slope due to the development of the growing fold. This contact is interpreted to be the surface expression of an active fold.

The above observations are significant because the contact of the thrust plane occurs very close to the epicentral zone of the Chamoli earthquake. Although the models for many earthquakes including that at Uttarkashi suggest the rupture along MCT-I, geological evidences for active faulting in this region are sparse. From this view point, observations in the epicentral region of the Chamoli earthquake may provide guidelines to identify active faults/folds in the Himalaya.

### ***Historic and Current Seismicity***

Historic and instrument data suggest fewer large earthquakes in the region compared to the rest of the Himalaya (*Figure 3*). One earthquake, probably of  $M > 7$ , is reported to have occurred in this region on 1 September 1803. Several villages are reported to have been buried by the rockfalls and landslides caused by that earthquake. The Badrinath temple located ~40 km north of Chamoli was severely damaged during that earthquake. Even though its location remains uncertain, intensity reports suggest that the 1803 event may have occurred in the same region affected by the current earthquake.

During the post-earthquake survey of the Chamoli earthquake, two temples, one at Gopeshwar and the other at Makkumath, built during 7-12<sup>th</sup> century were examined. These show evidences of severe damage during the 1803 event. Many parts of these two temples have been reconstructed as indicated by the inscriptions on their wall stones. Both these temples suffered only minor vertical cracks during the current earthquake, in spite of them being located in the meizoseismal area. This indicates that magnitude of the 1803 event may have been much larger.

The limited instrumentally recorded data from this region suggest a north-west oriented zone of moderate activity (*Figure 3*). Occurrence of two  $M > 6$  earthquakes within a span of eight years, a larger event 196 years ago and the clustered micro-seismicity indicate strain accumulation in the region. The 700-km-long seismic gap between the rupture zones of two great earthquakes, namely the 1905 Kangra ( $M8.6$ ) and the 1934 Bihar ( $M8.4$ ), generally referred to as the 'Central Gap,' is considered to be a potential area for a great earthquake (*Figure 1*). An alternate view is that the strain in this stretch was partially or totally released by the moderate earthquakes in the past. In this context, the mechanism of large earthquakes in the region and their relation to strain accumulation on MCT needs to be understood in greater detail.

### *Co-seismic Observations*

The Chamoli earthquake was accompanied by severe ground deformations. Development of ground fissures, landslides and changes in the groundwater flow were reported from several locations. Well-developed ground cracks trending roughly in the east-west direction and showing lateral movement of up to about 12 cm were observed in Gopeshwar, Chamoli and Bairagna. Attempts were made to make trenches across some of these ground fissures at the Telecom Hill, Gopeshwar (*Figure 5*). None of the trenches could be extended down more than a meter, as these were bottomed on the rubbles or boulders, which form part of debris. In one of these trenches, a poorly defined thrust plane was detected. Orientation of these ground fissures, although discontinuous, conforms to the strike of the thrust front (MCT-I). Majority of these east-west oriented fissures, particularly those developed in the well-consolidated debris, may be a manifestation of the fault movement.



*Figure 5:* Ground fissure at Telecom Hill near Gopeshwar

Ground cracks at several places also developed as part of slope failure and these pose threat to the down-slope settlements. Cracks were seen in asphalt roads at some locations, indicating the possibility of failure due to ground slippage. At several sites, large-scale earthquake-induced landslide/rock falls were observed (*Figure 6*). Those near Gopeshwar, Chamoli and Gadi continued

even after a fortnight of the event. Interestingly, these rockslides are also confined to locations along MCT-I.



*Figure 6:* A major landslide about 1km north of Gopeshwar. It blocked the road traffic to Okhimath for a considerable period.

In many ground water springs, flow increased by as much as ten times, surpassing even the post-monsoon discharge. On the contrary, at village Bairagna, the flow decreased and the water became muddy, indicating possible fluidization and remobilization of fine sediments.

#### ***Intensity Distribution, Site Effects and Strong Motion Records***

Figure 4 shows the intensity of shaking at some of the locations. The maximum intensity was VIII on MSK scale (at Upper and Lower Chamoli and at Upper Birahi). Intensity showed rather abrupt changes from one location to the other, because of the site effects on river terraces composed of alluvial deposits of sand and boulders. For instance, the right bank of the Birahi Ganga river has two settlements: Upper and Lower Birahi about 1 km apart. The intensity of shaking was VIII at Upper Birahi located on the river terrace at a higher elevation, whereas it was only VI at Lower Birahi on hard rock. A forest department check-post just across the river from Lower Birahi also showed higher intensity (VII) due to its location on the river terrace. The intensity at Lower and Upper Chamoli was VIII, and that at Gopeshwar, located only 2 km aerial distance

away, was only V. While Chamoli is located on the river terrace, Gopeshwar is at a higher elevation on the hill slopes. Intensity VII observed at Makkumath located also on a river terrace about 20 km aerial distance from the epicenter is another example of site amplification due to alluvial cover.

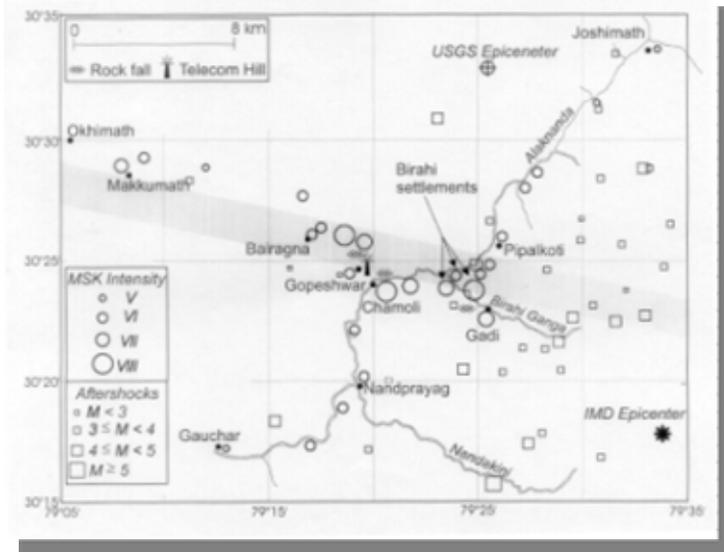


Figure 4: Intensity variation during the main shock and location of aftershocks in the affected area. Shaded portion shows the trend of the fault as per the fault-plane solution, which is consistent with the damage distribution.

The area has a number of analog strong motion accelerographs operated by the University of Roorkee. Strong motion records were obtained at Gopeshwar (9 km away from the epicenter), Joshimath (27 km), Okhimath (25 km) and Tehri (80 km). The peak ground acceleration in the two horizontal and the vertical directions at these locations are: Gopeshwar (0.20g, 0.36g, and 0.16g), Joshimath (0.071g, 0.063g, 0.041g), Okhimath (0.091g, 0.096g, 0.047g), Tehri (0.054g, 0.062g, 0.034g). The acceleration time history at Gopeshwar shows a large pulse, typical of near-source ground motions.

Even though the 1991 Uttarkashi and the present Chamoli events are of comparable magnitude and focal depth, the damage was much lower in the latter. Several factors may have contributed to this. Villages in Uttarkashi are located on well-developed river terraces of Bhagirathi river making them more vulnerable to site effects as compared to Chamoli where the river terraces are not so well developed. The Uttarkashi earthquake took place in October immediately after the monsoons which lead to much higher incidents of slope failures and

foundation movements. Finally, the construction practices in Chamoli area are much better, in comparison to what existed in Uttarkashi in 1991.

### *Behaviour of Buildings*

In addition to numerous villages, the affected area has several small townships along the major roads. Many of the villages are not connected by motorable roads and are accessible only after considerable trekking. The building stock in the affected area consists primarily of rural dwellings, with some urban houses and a few modern constructions for office or commercial purposes in towns. Load-bearing random rubble stone masonry in mud mortar formed the predominant wall system employed in the area. Many constructions of the recent years have been in brick or concrete block masonry in cement mortar. The roofing system is usually thatch, tin sheets, slate tiles, or RC slabs. In general, most roofs are pitched. Also, in the recent years, many reinforced concrete (RC) frame buildings with masonry infill walls have come up in the towns. To accommodate the ground slope, the buildings often have less number of storeys on the hill side and more on the valley side. In general, most constructions are non-engineered with no formal involvement of engineers in design or construction. However, the style of construction has improved over the years and many newer constructions, even in remote villages, have RC lintel band for protection against earthquakes: a result of the awareness created by the 1991 Uttarkashi earthquake. Indian seismic codes (e.g., IS:4326-1993, IS:13827-1993) recommend lintel band, in addition to other features, for improving the seismic performance of load-bearing constructions. After the 1991 earthquake compliance of the seismic code provisions in the government constructions in this region may have improved and this may have been picked up by the villagers through common contractors and masons. This earthquake provided a good opportunity to evaluate the efficacy of lintel bands.

### *Traditional Stone Dwellings*

The traditional dwellings in the area are usually of one or two storeys with a rather low storey height (about 1.65m). The walls are about 0.45-0.60m thick in stone masonry with mud mortar and are usually of two types:

- (a) *Random rubble stone masonry using the undressed stones:* The wall is made of two separate sections, the outer and inner wythes, so that both surfaces are smooth. The space between the two wythes is filled with stone rubble.
- (b) *Masonry with slate wafers:* Dressed stones (about 0.3m long, 0.15-0.2m wide and 0.12m thick) and slate wafers (about 0.3m long, 0.15-0.2m wide and 0.005-0.020m thick) are stacked tightly with very little or no mud mortar in

between. In carefully done walls of this type, the dressed stones appear at intervals of about 0.5m along the length and about 0.3m along the height, else they appear at random locations. Unlike in case of random rubble masonry, the rubble of small stones is not dumped in the middle region of the wall. Since none of the slate wafers is wide enough, this type of wall also has a tendency to split and buckle into two separate wythes due to lack of interlocking (*Figure 7*).



*Figure 7:* Collapse of one of the wythes in a traditional house in slate wafer masonry.

Most of the dwellings have wood rafter roof supported directly on the walls. Many very old constructions and a few new constructions have wood rafter roof supported on vertical wooden posts. Relatively new constructions often use reinforced concrete roof directly resting on the walls.

These dwellings have heavy roof mass and rather weak walls, and these performed poorly as expected (*Figure 8*). Most of the deaths and injuries occurred due to the collapses of such units. In fact, many older buildings owned by the government also fall in this category. The police lock-up at Upper Chamoli consisted of random rubble masonry in cement mortar; collapse of this building killed six inmates and injured about twelve persons. However, the dwellings with masonry walls in slate wafers performed better than those in random rubble masonry. The most common damage pattern was the separation of wythes following which the walls tended to buckle. Where wood rafter roofs were used, partial cave-in of the roof along with the wall was also frequently

observed. Most constructions using wooden post system for supporting roof were able to withstand the motion without collapse. However, the walls of these structures were extensively damaged, and the houses were left unfit for occupation.



Figure 8: Partial collapse in a random rubble stone masonry. Note that the front portion has RC beam supported on concrete block columns and roof consists of RC slab

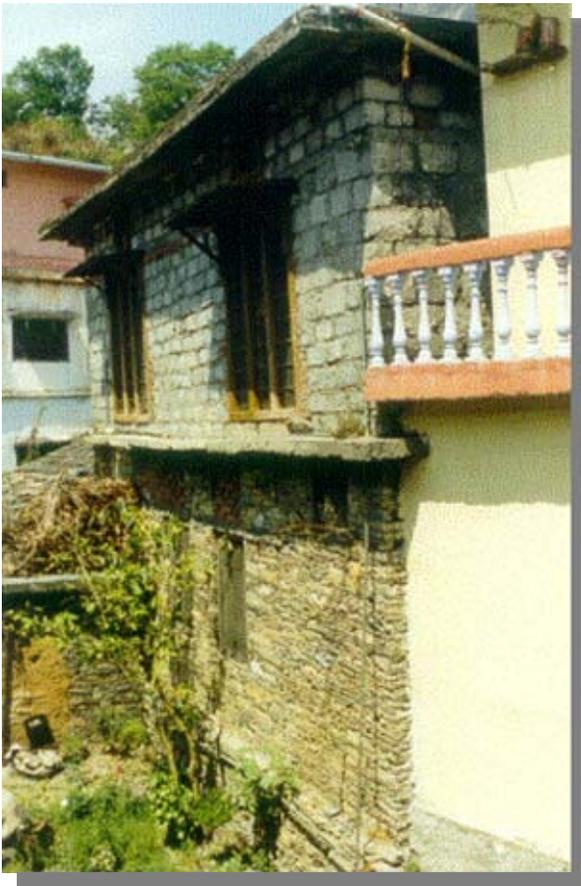
#### *Brick or Concrete Block Masonry Buildings*

Several relatively new buildings in rural as well as urban areas are in burnt brick masonry in mud or cement mortar. Since such bricks require long-distance transportation from the plains, concrete block masonry is another form of construction becoming popular in the area. In such buildings, the roof is usually in reinforced concrete. The performance of such buildings has in general been much better than that of the stone masonry buildings.

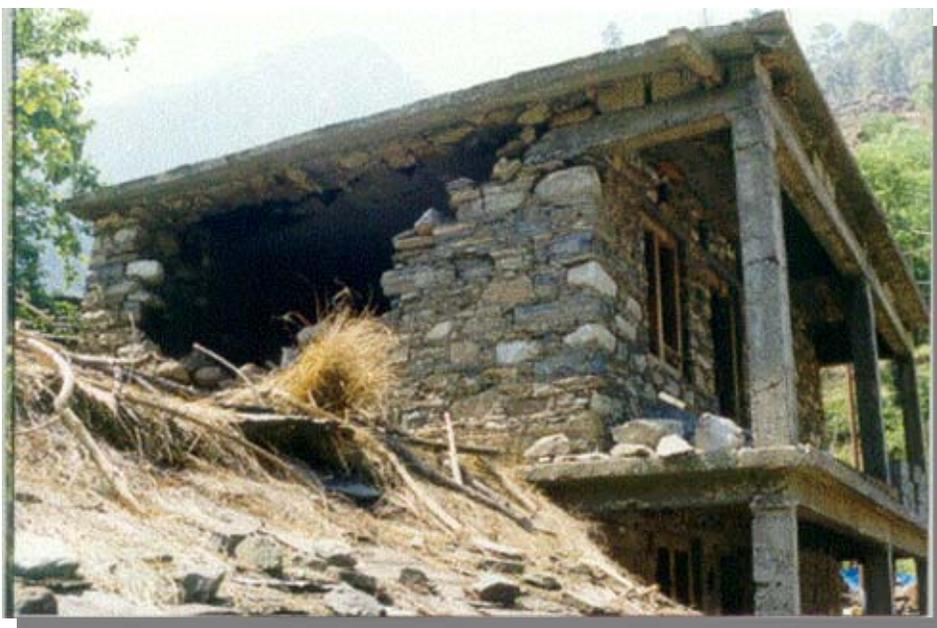
An interesting example of the *short-column effect* was observed at the passenger waiting hall at Bedubagad (intensity VI), about 2km from Birahi towards Chamoli. This is a newly-constructed single-storey concrete block masonry structure with an RC roof. Along the perimeter of the hall, masonry walls were raised between the columns up to half the storey height. At the north-east corner, a room has been provided for office space making the building torsionally unbalanced. The columns along the periphery became *short columns* as compared to the interior ones and sustained more cracking. Moreover, the columns on the west side sustained greater damage than those on the east side due to the torsional effect.

### *Masonry Buildings with Lintel Band*

Numerous dwellings built in recent years in villages as well as in towns are provided with a reinforced concrete lintel band. These include both stone masonry buildings and brick/concrete block masonry buildings (*Figure 9*). Often the rooms are provided with a RC shelf (about 0.45 m wide) projecting from the wall at lintel level; it serves the dual purpose of a storage slab and a lintel band. Most houses with lintel band performed very well, even though the quality control in these dwellings may not have been very good. Some buildings with lintel band that sustained damage had serious flaws with continuity of the band (*Figure 10*).



*Figure 9:* Two-storey house at Pipalkoti with no damage. Ground storey in slate wafer masonry, upper storey added later in concrete block masonry. Both storeys have RC lintel band



*Figure 10:* Partial collapse in a stone masonry house at Gadi village. Lintel band, present in the front portion, does not continue in the side wall

### *RC Frame Buildings*

There are many RC frame buildings with brick infills in the affected area. Gopeshwar, being the district headquarters, has numerous such buildings up to four storeys. Such buildings performed very well even though most of these were not formally designed, and certainly not for seismic loads. The common form of damage included separation cracks at the interface of the RC frame and infill panels, and cracking of infills. This is in line with what has been experienced in the 1991 Uttarkashi (M6.5) and 1997 Jabalpur (M6.0) earthquakes in India. These buildings have simple structural configuration and are characterized by small spans and small openings. The masonry infills therefore act more like shear walls and not as non-structural elements. In fact, at times, the construction of the masonry walls and the reinforced concrete progresses simultaneously so as to save on the form work for the beams and columns. Clearly, such buildings tend to be more like load bearing wall type constructions with columns acting as corner reinforcement and beams acting as a roof band.

Interestingly, a number of such RC frame buildings were also found to have RC lintel bands. This is the result of a rather common confusion in some seismic regions of the country where code requirements of lintel band in masonry buildings are assumed to be applicable also to the RC frame buildings with masonry infills. Many buildings were seen in the region with about 15 cm to 30 cm length of column reinforcement projecting above the roof for future vertical

extension. Such buildings, if extended vertically, can be a major problem in future earthquakes due to inadequate lap length.

### *Building Damage at Far Off Places*

An interesting aspect of this earthquake was that a few buildings in Delhi (280 km aerial distance from epicenter) sustained some non-structural damage. For instance, Tarang Apartments (*Figure 11*), an eight-storey building with open ground storey, in Patpatganj area located on the banks of the Yamuna river, sustained cracks in infill walls and separation of infills from RC frame at the lowest storey. These damages, even though minor, underline the disaster potential of Delhi not only from the nearby damaging earthquakes, but also from the large events in the far-off Himalaya. Many buildings in Dehradun (125 km west of Chamoli town) sustained damage. For instance, some old buildings of the Survey of India sustained collapse of gable masonry, and severe cracking along the junctions between the pitched roof and the masonry walls.



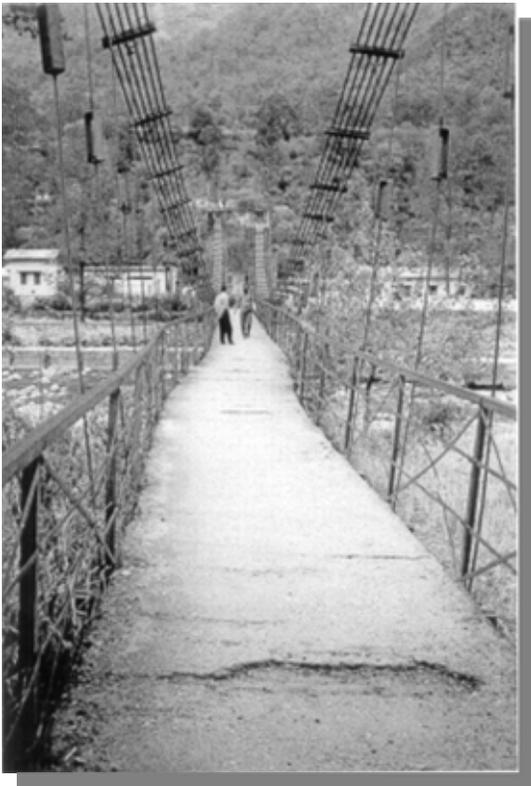
*Figure 11:* Tarang Apartment in Delhi that sustained damage due to infill walls

### *Behaviour of Lifelines*

There is no rail network in the region, but there is a good road network along the mountains. Hence, there are number of road bridges, mostly single span and in a few cases multi-span. The superstructure is either a steel truss or a reinforced concrete girder. The abutments are of stone masonry, and intermediate piers in the multi-span bridges of reinforced concrete. The connection between the superstructure and substructure consists of rocker and roller bearings. Most

bridges performed well even though this cannot be taken to mean that bridges as built in the area have adequate seismic resistance. Intensity of shaking experienced by these is much lower than what is expected in seismic zone V.

The area has numerous pedestrian bridges across the rivers; some of these are of suspension type with span ranging from 15m to 60m. Lateral buckling of the bridge deck was observed at one of the pedestrian suspension bridges located near Bairagna (*Figure 12*). The cables were found to have loosened, possibly due to shifting of the anchor block at one end due to slope instability.



*Figure 12: Lateral buckling of the deck of a suspension bridge at Bairagna*

The area lost electrical power a few seconds after the earthquake; in some areas it took as much as a week to restore the power. The telecommunication system continued to function after the earthquake. A 20m high communication tower in steel truss located on the Telecom Hill at Gopeshwar did not show any distress.

Water supply in the area is by collecting water from the springs into tanks at higher elevations and distributing it through a network of pipes. Water supply to Chamoli and Gopeshwar towns was disrupted due to damage to the pipelines by the landslides. It took about a week to restore most of the water supply lines. The affected area has a minor irrigation network consisting of typically 0.4-0.5 m

wide and equally deep concrete-lined canals. The lining of the canals cracked at several locations but no major damage to the system was reported.

### *Emergency Response*

Fortunately, the number of fatalities in the earthquake was relatively less at about 100 as compared to about 800 in the 1991 Uttarkashi earthquake. Interestingly, at the time of earthquake a popular movie was being screened by a TV channel and many people who were awake could easily escape. The area has major Hindu shrines and draws huge tourist traffic during May to October; the timing of this earthquake was fortunately during the lean tourist season. Hence, the task of search and rescue operations was easier and was carried out by the local people. Army and paramilitary personnel were also called-in to help in relief operations the very next day. Some cash compensation, food rations, and cloth tents were provided by the state government. By March the winter is over, and hence, cloth tents were sufficient for temporary shelters. Food and other supplies had to be air-dropped to numerous villages which were normally inaccessible by motorable roads or cut-off due to landslides. Due to poor accessibility, relief operations were quite challenging and caused dissatisfaction in remote villages which could not be attended to on time.

The headquarters for Chamoli district is at Gopeshwar, 10 km by road from Chamoli. Since Gopeshwar did not experience major damages, the entire administrative machinery could function effectively. However, frequent visits by senior politicians and administrators from the state and central governments may have significantly diverted attention of the district officials. Damage assessment for individual houses was initiated by the revenue officials immediately after the earthquake. This was also a difficult task due to the inaccessibility of many villages leading to some complaints about the fairness in damage assessment.

Significant aftershock activity, which included a few events of  $M > 5$ , created a lot of fear amongst the people and they hesitated to sleep indoors even when their dwellings had little or no damage. Speculations about an impending large earthquake added to the fear and panic. Massive forest fires, which are common during this time of the year, drove some wild animals towards the villages adding to the insecurity. Impending monsoons in the next two months remained a major concern; slope failures and additional damage to partially damaged houses were feared.

### *Some Important Issues and Recommendations*

This earthquake caused moderate shaking of intensity up to VII-VIII on MSK scale in an area that lies in the most severe seismic zone V. Indian code implies that areas in zone V are prone to shaking intensity of IX and above. In that sense, the affected area suffered a much lower intensity of shaking than what its potential is. Even though the damage is quite limited in its extent and nature, this earthquake has taught several lessons and raised some important issues. These include:

- a) While the traditional stone houses performed poorly as expected, the satisfactory performance of constructions with lintel bands clearly establishes their efficacy.
- b) The performance of RC frame buildings with brick infills has once again demonstrated that brick infills can be an asset rather than a liability for ordinary buildings without configuration irregularities. This is important for building practices in many developing countries. Efforts are needed to develop suitable design procedures for such buildings.
- c) Non-structural damage to some buildings in far-off Delhi clearly underlines the potential for a major disaster in Delhi from not just nearby damaging earthquakes but also from large events in the Himalaya. Considering the political and other significance of such an eventuality, efforts should be directed for an effective earthquake disaster mitigation and management in the Indian capital.
- d) Although the Uttarkashi and Chamoli earthquakes were of comparable magnitude and focal depth, the latter caused much lower damage and casualty. It is postulated that site characteristics of the regions may be an important reason for this discrepancy. The extensive and well-developed river terraces on which the villages of Uttarkashi are located may have played a major role in ground shaking characteristics.
- e) The earthquake provided clear demonstrations of site effects at several locations wherein the damage intensity was much higher on alluvial deposits than at the nearby rock sites. In view of several  $M > 5$  aftershocks, quick deployment of mobile strong motion accelerographs in large numbers could have provided excellent information on site characteristics; unfortunately, this opportunity was missed.
- f) This area seems to have experienced a much larger and more damaging earthquake in 1803; this leaves no room for complacency. Two parallel initiatives are urgently needed: a massive earthquake disaster reduction programme by strengthening the existing housing stock, and a better assessment of the earthquake hazard by way of paleoseismic and other studies.

- g) The earthquake took place in an area known for its seismogenic potential, and yet appropriate plans to handle such an eventuality were not available a priori. Uttarkashi and Chamoli earthquakes have taught many lessons. These need to be integrated to develop an earthquake disaster management plan for the entire Himalayan belt.
- h) This earthquake has provided an excellent opportunity to carry out a significant seismic rehabilitation and strengthening programme in the entire Garhwal area, and not just in the worst affected villages. This will go a long way in long-term earthquake disaster reduction in the area. The fact that villagers on their own have been adopting lintel band constructions shows that the local population will be quite receptive to a systematic programme in this direction.

Five moderate earthquakes of magnitude around 6.5 occurred in India since 1988; this leaves the country with no choice but to develop a strong and meaningful activity in earthquake disaster preparedness, mitigation and management. Towards this end, a beginning should be made by developing a white paper on the status of earthquake science and engineering in the country.

#### *Acknowledgements*

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