Learning from Earthquakes

The Chamoli, India, Earthquake of March 29, 1999

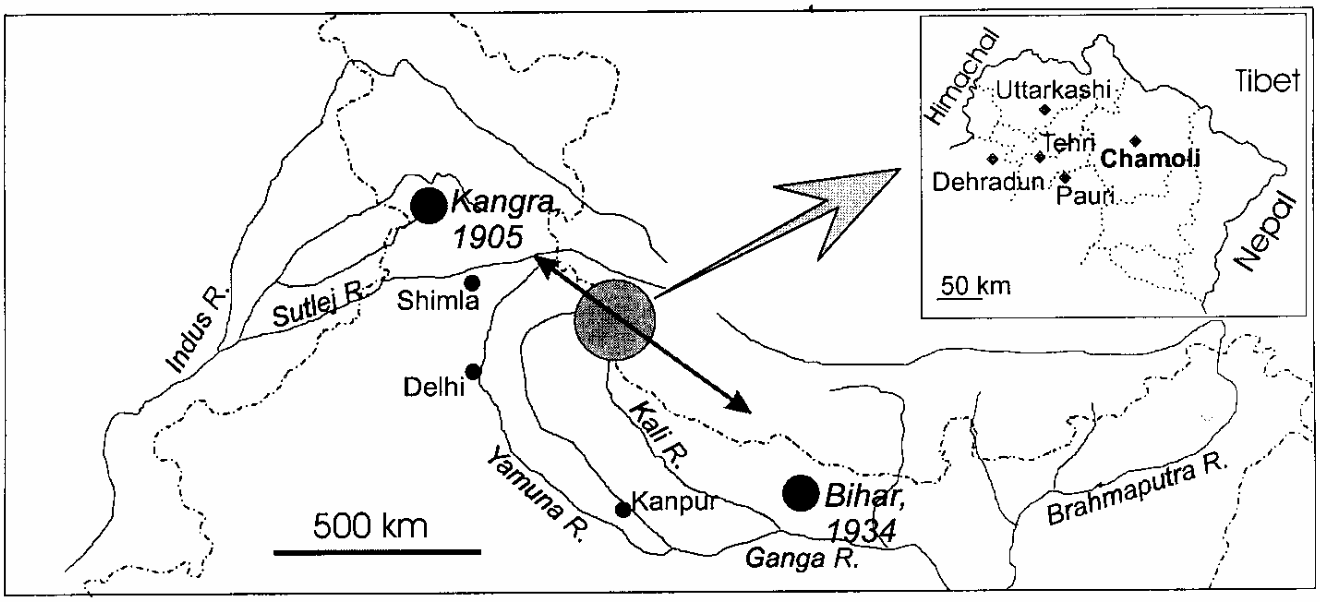

Figure 1: *Sketch of northern India showing locations of two great earthquakes, Kangra (1905) and Bihar (1934). The area marked with double arrows between these earthquakes is the Central Seismic Gap.* ***Insert:*** *Parts of Uttar Pradesh state and the location of the town of Chamoli, close to the epicenter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

The research, publication, and distribution of this report were funded by the National Science Foundation as part of EERI's Learning from Earthquakes Project under Grant #CSM-9526408.

Introduction

The Chamoli earthquake in northern India is an important event from the viewpoint of Himalayan seismotectonics and seismic resistance of nonengineered construction. The earthquake hit in a part of the Central Himalaya that is highly prone to earthquakes and has been placed in the highest seismic zone (zone V) of India. (There has been controversy during 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 MSK intensity reached VIII at a few locations. The earthquake caused approximately 100 deaths and hundreds of injuries.

Two separate groups carried out the postearthquake investigation. A five-member group conducted a nine-day survey of the 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, conducted a six-day survey of the meizoseismal area four days after the event. The Earthquake Engineering Research Institute sponsored the visits of the above persons as part of the *Learning from Earthquakes* project funded by the National Science Foundation. This report summarizes observations on the seismotectonic setting of the earthquake, the behavior of structures, and emergency response.

General Aspects of the Earthquake

The earthquake occurred on March 29th at 12:35 am (local time) near the town of Chamoli in the state of Uttar Pradesh in northern India (Figure 1). The earthquake magnitude was calculated as mb=6.3, MS=6.6 by USGS, and as mb=6.8, MS=6.5 by the India Meteorological Department (IMD). The preliminary locations of the epicenter by the different agencies are 30°49.2′N, 79°28.8′E by USGS; and 30°17.82′N, 79°33.84′E by IMD. Distances in this report refer to the USGS location.

Recorded aftershocks and the damage pattern suggest that the zone of activity was close to Chamoli; this region also showed a maximum intensity of VIII on the MSK scale. USGS estimated the focal depth at 12 km. The quake was felt at far-off places such as

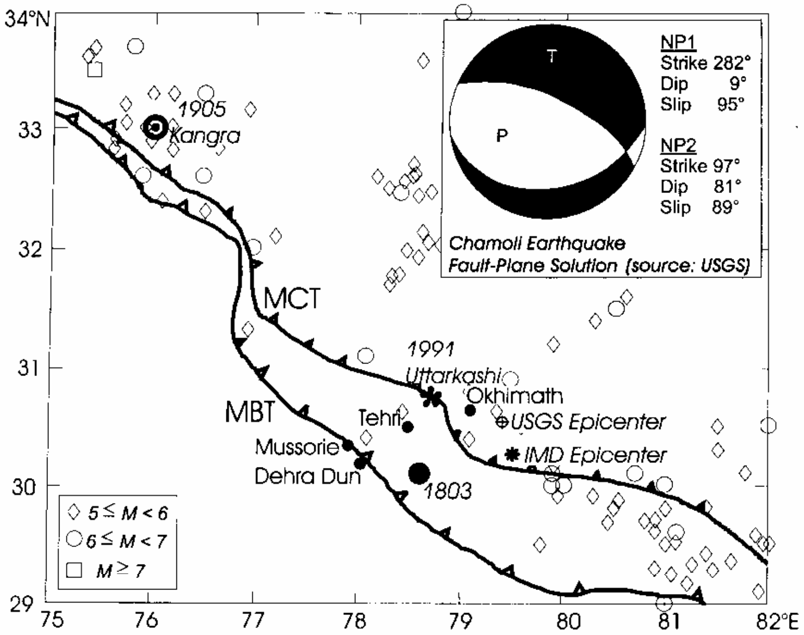

***Figure 2:** Spatial pattern of seismicity in Garhwal Himalaya during 1684-1985 with respect to two of the major thrusts MCT and MBT [Khattri et al., 1989, Proc. Indian Acad. Sci. (Earth. Planet. Sci.), 91-109]. The subsets MCT-I, II, III are not marked. Shaded circle indicates the maximum felt area of the 1803 earthquake. **Insert:** Fault-plane solution of the main shock at Chamoli.*

Kanpur (440 km southeast of the epicenter), Shimla (220 km northwest) and Delhi (280 km southwest). Maximum death and damage occurred in the district of Chamoli, where about 63 persons died and over 200 were injured. About 2,595 houses collapsed and more than 10,850 were partially damaged. In all, about 1,256 villages were affected. A few buildings at the distant city of Delhi sustained nonstructural damage. No instances of liquefaction were reported. Linear 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 three events of M >5. Most of the aftershocks were located to the east of Chamoli. The fault plane solution obtained from USGS (Figure 2, insert) indicates a pure thrust mechanism with two nodal planes striking at 282° and 97°. The first one is preferred because it conforms to the field observations.

Geologic and Tectonic Setting

The Himalayan mountain range, an outcome of the compressional processes ensuing from 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 2.

The MCT is believed to have resulted from 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 northwest of Chamoli, is considered to be associated with this fault, as is the Chamoli quake. Observations of recent deformation in the epicentral region also support this association.

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 geologic maps of the area indicate the presence of an anticlinal structure very close to Chamoli. During the postearthquake field investigation, signatures of recent deformation associated with this anticline were observed. A sharp contact of MCT I with 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.

These observations are significant because the contact of the thrust plane occurs 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, geologic evidence for active faulting in this region is sparse. Observations in the epicentral region of the Chamoli earthquake may provide guidelines to identify active faults and folds in the Himalaya.

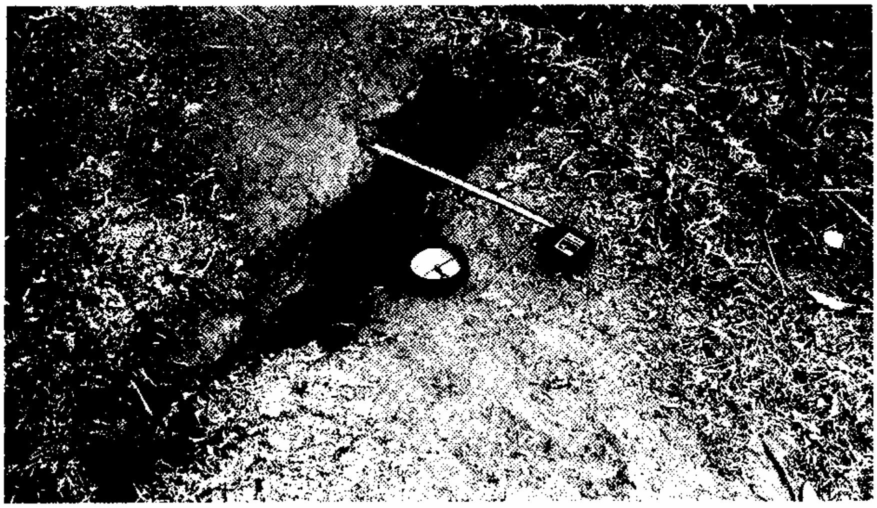

Figure 3: *Ground fissure at Telcom Hill near Gopeshwar.*

Historic and Current Seismicity

Historic and instrumental data suggest fewer large earthquakes in the region compared to the rest of the Himalaya (Figure 2). One earthquake, probably of M >7, is reported to have occurred in this region on September 1, 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. Even though the earthquake's location remains uncertain, intensity reports suggest that the 1803 event may have been in the same region affected by the current earthquake.

The postearthquake survey of the Chamoli earthquake examines two temples—one at Gopeshwar and the other at Makkumath, built during the 7 to12th centuries. These show evidence 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. That these temples suffered only minor vertical cracks during the current earthquake, in spite of being located in the meizoseismal area, indicates that the magnitude of the 1803 event may have been much larger.

The limited recorded data from this region suggest a northwest-oriented zone of moderate activity (Figure 2). 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 (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 mechanisms of large earthquakes in the region and their relation to strain accumulation on the MCT need to be understood in greater detail.

Co-Seismic Phenomena

The Chamoli earthquake was accompanied by severe ground deformations. 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 trench across some of these ground fissures at Telecom Hill, Gopeshwar (Figure 3), but none of the trenches could be extended downward more than a meter because of debris and boulders. In one of these trenches, a poorly defined thrust plane was detected. Orientation of these discontinuous ground fissures conforms to the strike

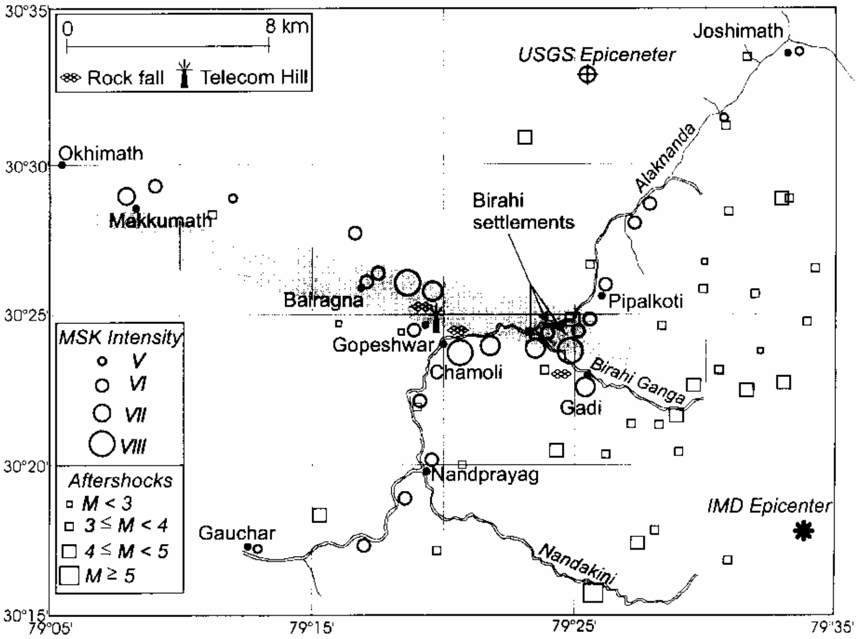

Figure 4: *Intensity variation during the main shock and location of aftershocks in the affected area. Shaded portion shows the trend of the fault from the fault-plane solution, which is consistent with the damage distribution.*

of the thrust front (MCT I). The majority of these east-west-oriented fissures, particularly those developed in the well-consolidated debris, may be a manifestation of the fault movement. Ground cracks at several places also developed as part of slope failure, and these pose threats 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 landslides and rock falls were observed. Those near Gopeshwar, Chamoli and Gadi continued a fortnight after the event. Interestingly, these rockslides are also confined to locations along MCT I.

In many groundwater springs, flow increased by as much as ten times, surpassing even the post-monsoon discharge. However, at Bairagna village, 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 locations. Intensity showed rather abrupt changes from one location to another, because of 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 on the river terrace at a higher elevation, whereas it was VI at Lower Birahi on hard rock. A forest department checkpost 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, but at Gopeshwar, located 2 km away, it was V. While Chamoli is located on the river terrace, Gopeshwar is at a higher elevation on the hill slopes. The intensity VII observed at Makkumath, located on a river terrace about 20 km from the epicenter, is possibly another example of site amplification due to alluvial cover.

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 from the epicenter), Joshimath (27 km), Okhimath (25 km) and Tehri (80 km). The peak ground accelerations in the two horizontal and the vertical directions at these locations follow: 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.

Though the 1991 Uttarkashi and the present Chamoli events are of comparable magnitude and focal depth, damage was much less in Chamoli for several reasons. The villages in Uttarkashi are located on well-developed river terraces of the Bhagirathi River, making them more vulnerable to site effects as compared with Chamoli, where the river terraces are not so well-developed. The Uttarkashi earthquake took place in October immediately after the monsoons, which lead to a much higher incidence of slope failure and foundation movement. Finally, construction practices in the Chamoli area are much better than those in Uttarkashi before 1991.

Building Behavior

Many of the villages in the affected area are not connected by passable roads and are accessible only after considerable trekking. In addition to these villages, the area has several small townships along the major roads.

The building stock consists primarily of rural dwellings, with some urban houses and a few modern structures for office or commercial purposes. Load-bearing random rubble stone masonry in mud mortar formed the predominant wall system employed in the area. Much of the construction of recent years has been in brick or concrete block masonry using cement mortar. The roofing system is usually thatch, corrugated galvanized iron sheets, slate tiles, or reinforced concrete (RC) slabs. In general, most roofs are pitched.

***Figure 5:** Collapse of one of the wythes in a traditional house in slate wafer masonry.*

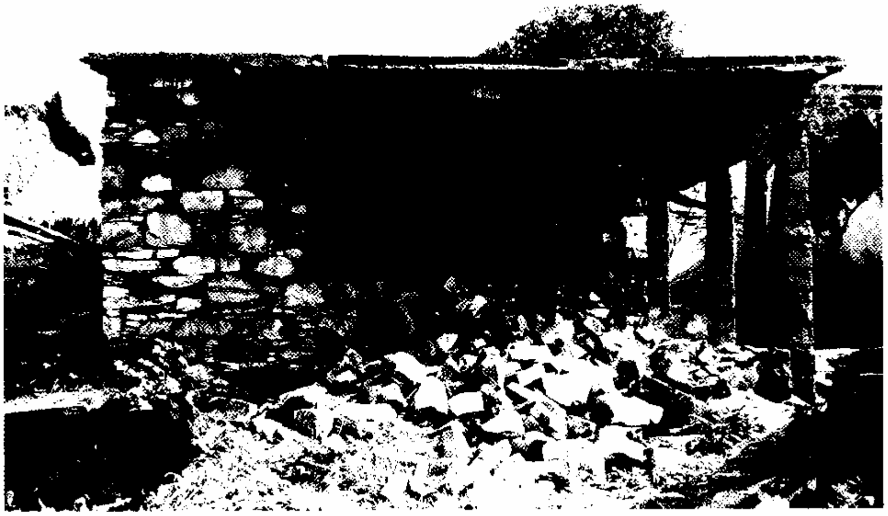

Figure 6: *Partial collapse in a random rubble stone masonry building. Note that the front portion has RC beam supported on concrete block columns, and the roof consists of an RC slab.*

In recent years, RC frame buildings with masonry infill walls have been built in the towns. To accommodate the ground slope, the buildings often have fewer stories on the uphill side than on the valley side. In general, most construction involves no formal contributions from engineers. However, the style of construction has improved over the years and much newer construction, even in remote villages, has an RC lintel band for protection against earthquakes. This is the result of 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 construction. After the 1991 earthquake, compliance with seismic code provisions in government construction in this region may have improved. In turn, the villagers may have picked this up through common contractors and masons. This earthquake provided a good opportunity to evaluate the efficacy of lintel bands.

1. Traditional Stone Dwellings. Traditional dwellings in the area are usually of one or two stories, with a rather low story height (about 1.65 m). The walls are 0.45-0.60-m thick using stone masonry with mud mortar and are usually of two types:

(a) *Random rubble stone masonry using undressed stones.* The wall is made of two separate sections, the outer and inner wythes, so that both exposed surfaces are smooth. The space between the two wythes is filled with stone rubble.

(b) *Masonry with slate wafers.* Dressed stones (about 0.3 m long, 0.15-0.2 m wide and 0.12 m thick) and slate wafers (about 0.3 m long, 0.15-0.2 m wide and 0.005-0.020 m 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 0.5 m along the length and about 0.3 m along the height. Unlike the case with random rubble masonry, small stones are not dumped in the middle region of these walls. 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 5).

Most of the dwellings have a wood rafter roof supported directly on the walls. Many very old structures and a few new ones have a wood rafter roof supported on vertical wooden posts. Relatively new construction often uses a reinforced concrete roof supported directly on the walls. These dwellings have a heavy roof mass and rather weak walls and they performed poorly, as expected (Figure 6), causing most of the deaths and injuries. Many older buildings owned by the government also performed badly. The police lock-up at Upper Chamoli consisted of random rubble masonry in cement mortar; the collapse of this building killed six inmates and injured about 12 others.

The dwellings with masonry walls in slate wafers performed better than those with 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 construction that used wooden posts for supporting the roof was able to withstand the motion without collapse. However, the walls of these structures were extensively damaged, and the houses were left unfit for occupation.

2. Brick or Concrete Block Masonry Buildings. Several relatively new buildings in rural and urban areas use burnt brick masonry with mud or cement mortar. Such bricks require long-distance transportation from the plains, so concrete block masonry is becoming popular in the area. In such buildings, the roof is usually of 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 2 km from Birahi towards Chamoli. This is a newly constructed single-story concrete block masonry structure with an RC roof. Along the perimeter of the building, masonry walls were raised between the columns up to half the story height. At the north-

Figure 7: Two-story house at Pipalkoti with no damage. Ground story in slate wafer masonry, upper story added later in concrete block masonry. Both stories have an RC lintel band.

east corner, a room has been provided for office space, making the building unbalanced from a torsion aspect. The columns along the perimeter became short columns, compared with 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.

3. Masonry Buildings with Lintel Bands. Numerous dwellings built in recent years in villages and towns have reinforced concrete lintel bands. These include both stone masonry buildings and brick or concrete block masonry buildings (Figure 7). Often the rooms are provided with an RC shelf (about 0.45 m wide) projecting from the wall at the lintel level that serves the dual purpose of a storage slab and a lintel band. Most houses with lintel bands performed very well, even though the quality control in these dwellings may not have been good. Buildings with lintel bands that sustained damage had serious flaws with continuity of the band (Figure 8).

4. 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 stories high. 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 was experienced in the 1991 Uttarkashi (M6.5) and 1997 Jabalpur (M6.0) earthquakes. These buildings have simple structural configurations and are characterized by small spans and small openings. The masonry infills act more like shear walls and not as nonstructural 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 structures, with columns acting as strong corners and beams acting as roof bands.

Interestingly, a number of such RC frame buildings were also found to have RC lintel bands. This is the result of rather common confusion in some seismic regions of the country where code requirements of lintel bands in masonry buildings are assumed to apply also to the RC frame buildings with masonry infills.

Many buildings were observed with 15 to 30 cm of column steel reinforcement projecting above the roof for future vertical extension. Such buildings, if extended vertically, can be a major problem in future earthquakes due to this inadequate lap length.

Building Damage at a Distance

An interesting aspect of this earthquake was that a few buildings in Delhi (280 km from the epicenter) sustained nonstructural damage. For instance, Tarang Apartments (Figure 9), an eight-story building with an open ground story, sustained cracks in infill walls and separation of infills from the RC frame at the lowest story. This structure is located in the Patpatganj area on the banks of the Yamuna River. Even though minor, this damage underlines the disaster vulnerability of Delhi from both nearby damaging earthquakes and large events in the far-off Himalaya. Additionally, many buildings in Dehradun (125 km west of Chamoli) sustained damage. For example, in some old buildings of the Survey of India, the gable masonry collapsed and there was severe cracking along the junctions between the pitched roof and the masonry walls.

Lifelines

There is no rail network in the region, but there is a good road network along the mountains. Hence, there are numerous road bridges, mostly single span but in a few cases, multispan. 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 are of reinforced concrete. The connection between the superstructure and substructure consists of rocker and roller bearings. Though most bridges performed well, we cannot conclude that bridges as built in the area have adequate seismic resistance. The intensity of shaking experienced by the bridges is much lower than what is expected in seismic zone V.

The area has numerous pedestrian bridges across the rivers, some of which are suspension bridges with spans ranging from 15 m to 60 m. Lateral buckling of the bridge deck was observed at one of the pedestrian suspension bridges located near Bairagna (Figure 10). The cables were found to have loosened, possibly due to the shifting of the anchor block at one end where there was slope instability.

Figure 8: Partial collapse in a stone masonry house at Gadi village. The lintel band, present in the front portion, does not continue along the side wall.

Figure 9: Tarang apartment in Delhi that sustained damage to infill walls.

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

The water supply in the area comes from collecting water from springs into tanks at higher elevations and distributing it through a network of pipes. The water supply to the towns of Chamoli and Gopeshwar was disrupted because landslides damaged the pipes. 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 m to 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 fatalities in the earthquake numbered much fewer than the nearly 800 in the 1991 Uttarkashi earthquake. In addition to the possible technical reasons cited earlier, this may be due to some serendipity: at the time of the earthquake, a popular movie was being screened by a TV channel, so many people were awake and easily escaped their collapsing homes. Furthermore, the area has major Hindu shrines and draws huge tourist traffic from May to October, but the timing of this earthquake was during the off-season. Hence, the task of search and rescue operations was easier and carried out by local people. Army and paramilitary personnel were called in to help in relief operations the very next day. The state government provided some cash compensation, food rations, and cloth tents. Since the winter is over by March, cloth tents were sufficient for temporary shelters. Food and other supplies had to be air-dropped to numerous villages which were either normally inaccessible by vehicle, or were cut off due to landslides. Poor accessibility made relief operations challenging, and remote villages expressed dissatisfaction over the length of time it took for aid to reach them.

Headquarters for the Chamoli district is at Gopeshwar, 10 km by road from Chamoli. Since Gopeshwar did not experience major damage, 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 the attention of the district officials. Revenue officials initiated damage assessment for individual houses immediately after the earthquake. This was also a difficult task due to the inaccessibility of many villages, resulting in some complaints about fairness in damage assessment.

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

Important Issues and Recommendations

This earthquake caused moderate shaking of intensity up to VIII on the MSK scale in an area that lies in seismic zone V. The Indian code implies that areas in zone V are prone to shaking intensity of IX and above, so this earthquake caused a lower intensity of shaking than what is possible. Even though the damage is limited in its extent and nature, this earthquake has taught several lessons and raised some important issues.

a) While the traditional stone houses performed poorly as expected, the satisfactory performance of structures with lintel bands clearly establishes an improvement.

b) The performance of RC frame buildings with brick infills has once again demonstrated that brick infills may perform satisfactorily for ordinary buildings, without configuration irregularities, during M 6.6, MSK intensity VIII, events. This is important for building practices in many developing countries. Efforts are needed to develop suitable design procedures for such buildings.

c) Nonstructural damage to some buildings in far-off Delhi clearly underlines the potential for a major disaster there. Considering the political and social significance of such an eventuality, efforts should be directed towards 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 less damage and fewer casualties. It is postulated that 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 clearly demonstrated site effects at several locations where the damage intensity was much higher on alluvial deposits than at 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; there is no room for complacency. Two parallel initiatives are urgently needed: an earthquake disaster reduction program to strengthen 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. The lessons of the Uttarkashi and Chamoli earthquakes need to be integrated into 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 project in the entire Garhwal area, not only in the most affected villages. The fact that villagers on their own have been adopting lintel band construction shows that they may be receptive to a systematic program in this direction.

Five moderate earthquakes of around 6.5 magnitude have occurred in India since 1988; this leaves the country with no choice but to develop strong initiatives in earthquake disaster preparedness, mitigation and management. As a beginning, a white paper on the status of earthquake science and engineering in the country should be commissioned.

Figure 10: *Lateral buckling of the deck of a suspension bridge at Bairagna.*