THE MARCH 29, 1999 EARTHQUAKE AT CHAMOLI, INDIA

Manish SHRIKHANDE[1], Durgesh C RAI[2], Jayprakash NARAYAN[3] And Josodhir DAS[4]

SUMMARY

A moderate earthquake of Richter magnitude 6.8 rocked the Garhwal region of Western Himalayas on March 29, 1999 at 00:36:13.4 hours IST with espicenter at 30.408 ^{o}N, 79.416 ^{o}E near Chamoli/Gopeshwar. The tectonic set-up and seismicity of this region is discussed and the event was located in the active MCT zone and may have caused by a low angle fault. The extent and severity of damage was influenced by lateral heterogeneity and topography of the area. The strong motions in the epicentral region are found to be relatively rich in low frequencies indicating a deep focus event. Further, the prevalent construction practices in the region and their performance during the earthquake is discussed. Non-compliance to the earthquake-resistant features, and poor construction practices for locally available building materials were responsible for the majority of structural damage observed in the affected area

INTRODUCTION

The Garhwal-Kumaun region of Western Himalayas was rocked by a moderate earthquake, measuring 6.8 on Richter scale, on March 29, 1999 at 00:35:13.4 hours IST. The epicenter was located at 30.408 ^{o}N, 79.416 ^{o}E and the focal depth has been estimated to be 21 km. The region had also experienced a moderate earthquake in 1991 whose epicenter was located at 30.74°N, 78.79°E near Uttarkashi and the focal depth was estimated to be 19 km. The topography of the earthquake affected region is extremely uneven and the population density in the region is very low. The most common form of construction in the region is undressed stone masonry in mud mortar with heavy but flexible stone slab roofs. The rescue and relief operations were hampered due to difficult mountainous terrain and landslides triggered by the earthquake which blocked many travel routes.

The earthquake rocked the twin cities of Chamoli and Gopeshwar and the neighbouring district of Rudraprayag. The worst affected regions lie mostly in the Alakananda river valley. The distribution of intensity of shaking was rather patchy and the maximum intensity on damage-based MSK scale was noted between VII and VIII. The affected region lies in the seismic zone V of the highest risk of the Indian standard for establishing the criteria for earthquake resistant structures. The Code anticipates an intensity of IX or more in the seismic zone V.

This earthquake provided an opportunity to study the nature of strong ground motion in the Himalayas. The tectonic set-up and seismicity of the Garhwal-Kumaun region is first discussed in the following. An isoseismal map of the earthquake affected area has also been prepared on the basis of field observations. Next, some characteristics of the strong motion data recorded during this event are discussed. Various features of the typical constructions in the region and their performance during the earthquake are also reported.

SEISMOLOGICAL ASPECTS

Seismotectonics

The Garhwal-Kumaun Himalayan region lies between 28.0 to 30.5 °N, and 79.0 to 82.0 °E. In the Garhwal Himalayas and the adjoining region, three major tectonic units are separated from each other by Main Boundary Thrust (MBT) and Main Central Thrust (MCT). The outermost sub-Himalayas Tertiary belt is thrusted over by

[1] *Department of Earthquake Engineering, University of Roorkee, Roorkee, INDIA*
[2] *Department of Earthquake Engineering, University of Roorkee, Roorkee, INDIA*
[3] *Department of Earthquake Engineering, University of Roorkee, Roorkee, INDIA*
[4] *Department of Earthquake Engineering, University of Roorkee, Roorkee, INDIA*

the Proterozoic-Eocene sequence of the lesser Himalayas along MBT. To the south of this, the steeply north dipping Main Frontal Thrust (MFT) separates this belt from the Indo-gangatic plains. Molnar [1986] has given models concerning the evolution of the Himalayas and the role of the MCT and MBT/MBF in the uplift of these mountains. The lesser Himalayas sequence of the Proterozoic-Eocene rocks are dismembered into three distinct sub-units between the MBT and MCT in the Garhwal Himalayas [Jain 1987], *viz.*, North Almora Thrust (NAT), South Almora Thrust (SAT) and the Garhwal Thrust (GT). The low grade metamorphosed lesser Himalayas sediments are over ridden abruptly by medium to high grade schist, migmatite and gneiss belonging to Higher Himalayas Crystallines (HHC) along the northerly dipping MCT and their splays, such as Bhatwari Thrust (BT), Munsiari Thrust (MT) and the Vaikrita Thrust (VT) [Valdiya 1988].

The seismic activity in the Garhwal Himalayas is ascribed to northward movement of the Indian plate against the Tibet block of Eurasian plate at a rate of about 0.05-0.06 m/year [Molnar and Tapponnir 1975], deforming the rocks to form the higher Himalayas and making the area prone to seismic activity. The Garhwal-Kumaun region lies in a seismic gap between rupture zones of Kangra (1905) and Bihar-Nepal (1934) earthquakes. Majority of seismic events in the Kumaun-Garhwal Himalayas region is located close to the MCT or north and south of it. The earthquake shocks of magnitude 5 to 6 have been recorded in the Garhwal region in 1803, 1809, 1816, 1966, 1967, 1969, 1976, 1979, 1986, and 1991. Studies suggest that most of stress release due to micro-earthquake occur in the lesser Himalayas, i.e., inside or south of the MCT zone, which implies an accumulation of stress in the south of the MCT zone where micro-earthquake activity is relatively less [Khattri et al. 1989].

Intensity Distribution

Figure 1 shows the distribution of intensity of shaking where isoseismals of intensity VI and VII are drawn based on the local intensity value. Isoseismal map provides information regarding the nature of the earthquake, approximate focal depth and the epicenter and macro-seismic effects in the affected region. The maximum intensity VIII- was observed in two regions, namely; Devaldhar and Mandal valleys and Chamoli town in NE direction and Kyunja Tehsil and Dobalco village of Chandrapuri Tehsil in the SW from the epecenter. Intensity VIII- was assigned to Chamoli, Siroli, Makroli, Makku, Kansili and Dobalco villages/towns. The residents of these localities reported general panic, awakening and mixed sound of passing train, aeroplanes and thundering. In these localities a large number of ground fissures and landslides were also observed. Most of houses in these localities either were razed to ground or were partially collapsed and unsafe for living.

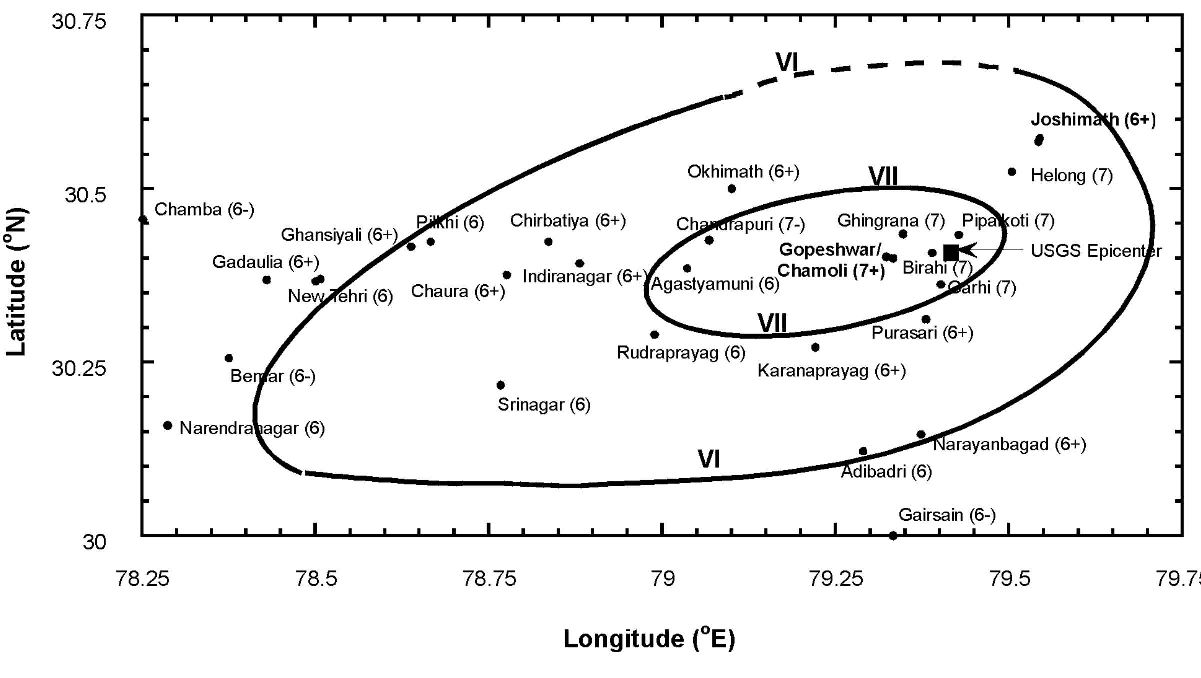


Figure 1. Isoseismal map

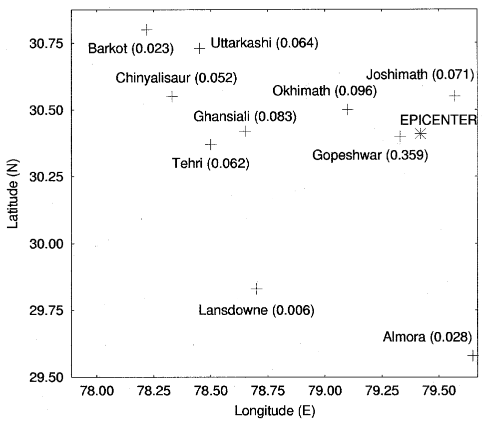
The intensity VII+ was assigned to Bhatwari-Sonar, Kyunja, Akhori, Pingala-Pani, Unali, Khada, Gondi, Bairagna, Badakoti, Pawaldhar, Bhargi, Urgam, Gopeshwar, Maithana, and Tilphara localities. Intensity VII was assigned to Mandal, Sirokhoma, Devaldhar, Markand, Gwan, Gighran, Pipalkoti, Helong and Sikari villages/

towns. The residents of these localities reported awakening, frightening, and mixed sound of passing train and thundering. In these localities landslides and ground fissures were fewer compared to the areas where intensity was VIII-. The lengths of major and minor axes of the elliptical isoseismal of intensity VII are about 50 km and 20 km, respectively. Isoseismal line for intensity VI is based on the intensity value of VI+ at Chandrapuri, Guptakashi, Okhimath, Tungnath, Tangni, Joshimath, Kathura, Chhemi, Trisula, Nandprayag, and Karnprayag; the intensity VI of Srinagar, Rudraprayag, Tilwara, Agastyamuni, Chopta, Pandukeshwar and intensity V+ and V of Deoprayag, Kanjal, and Badrinath. A few landslides and ground fissures were observed in these localities. The shape of the isoseismal VI is also elliptical and its anti-clockwise rotation may be due to Alakhnanda valley. The closer isoseismal lines in the ENE direction indicates rapid decrease of intensity in comparison to the WSW direction which can be attributed to the presence of harder crystalline rocks in the higher Himalayas and the comparatively softer rocks in the lower Himalayas.

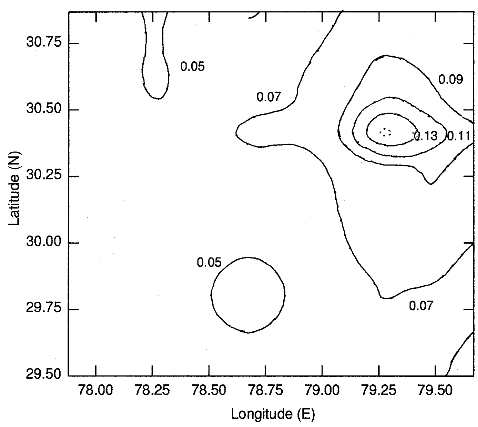
On the basis of damage pattern and the isoseismal map, it appears that the epicenter was within MCT zone between Alakhnanda and Mandakini valleys. The direction of ground fissures and landslides apparently have no relation with the direction of strike of the rupture and were mainly favoured by local conditions. The elongation of the isoseismal VII in WSW-ENE direction indicates that strike of the slip was almost in the same direction, because higher isoseismal lines are generally elongated along strike of the fault. Kaila and Sarkar [1978] have also drawn similar conclusion on the basis of isoseismal maps of 26 major Indian earthquakes and causative faults. For example, isoseismals of Kangra (1905), Bihar-Nepal (1934), Assam (1950) and Uttarkashi (1991) earthquakes were elongated in NW-SE, E-W, NE-SW and NW-SE directions, respectively, parallel to the Himalayan mountain chain in the various regions. The change in direction of the isoseismal VI may be caused by Alakhnanda Valley in almost NE-SW direction. The elongation of isoseismal lines along the river valley was also observed in Assam (1950), Calcutta (1964), Bihar-Nepal (1934) and Baluchistan (1909) earthquakes. This effect is generally observed on the isoseismal lines of lower intensity, whereas the shape of larger intensity isoseismals is governed by rupturing processes. Maximum damage in the strike direction at some distance from the epicenter and lesser damage near the epicenter in normal to strike direction indicates that the slip has been on a low angle fault. This effect is also observed in numerical studies of radiation patterns and simulation of various types of slip motions [Narayan 1998]. Empirical relation $I_o = 1.5M - 4.5 \log h + 4.5$ suggests a focal depth of about 25 km for the earthquake. The local topography and strong lateral heterogeneity have played a major role on the damage pattern in the region.

STRONG MOTION RECORDS

In view of high seismicity of the Himalayan region, the Dept. of Earthquake Engrg., Univ. of Roorkee, Roorkee, has deployed several strong motions recording instruments in the region. The Chamoli earthquake was recorded at 11 accelerograph stations including one in the epicentral region (at Gopeshwar). Figure 2a shows the location of epicenter of the mainshock and the accelerograph stations where the event was recorded. Figure 2b shows the contours of peak ground acceleration (PGA) in the region. It may be noted that the ground acceleration attenuates very rapidly, which was also observed in Uttarkashi earthquake [Chandrasekaran and Das 1991]. The rapid attenuation of ground vibration is primarily due to the presence of highly fissured rocks in the region. Some parameters of engineering significance for the motions recorded at eleven stations are shown in Table 1.



(a)



(b)

Figure 2. Location of strong motion stations and contours of PGA

Table 1: Strong ground motion characteristics of Chamoli (1999) earthquake

No.	Site	Component	PGA (g)	EPA (g)	I_A (10^{-2} gs)	P_D (10^{-3} gs^3)	f_c (Hz)
1.	**DEQ Roorkee**	N 55 W (L)	0.056	0.017	0.449	0.191	2.42
	Lat: 29.86 N	N 35 E (T)	0.047	0.015	0.333	0.127	2.56
	Long: 77.89 E	Vertical	0.017	0.006	0.073	0.007	5.23
2.	**Tehri**	N 63 W (L)	0.054	0.035	0.448	0.065	4.15
	Lat: 30.37 N	N 27 E (T)	0.062	0.031	0.429	0.723	3.85
	Long: 78.50 E	Vertical	0.034	0.015	0.132	0.009	6.02
3.	**Gopeshwar**	N 70 W (L)	0.199	0.117	2.952	1.322	2.36
	Lat: 30.40 N	N 20 E (T)	0.359	0.291	8.151	2.645	2.77
	Long: 79.33 E	Vertical	0.156	0.049	2.548	1.603	6.3
4.	**Okhimath**	N 15 E (L)	0.091	0.039	0.824	0.061	5.79
	Lat: 30.50 N	N 75 W (T)	0.096	0.046	0.837	0.415	7.1
	Long: 79.10 E	Vertical	0.047	0.025	0.198	0.099	7.06
5.	**Joshimath**	N 80 E (L)	0.071	0.02	0.339	0.444	4.37
	Lat: 30.55 N	N 10 W (T)	0.063	0.035	0.592	0.675	4.68
	Long: 79.57 E	Vertical	0.041	0.009	0.186	0.013	5.91
6.	**Chinyalisaur**	N 43 E (L)	0.052	0.03	0.365	0.062	3.84
	Lat: 30.55 N	N 47 W (T)	0.045	0.025	0.476	0.065	4.29
	Long: 78.33 E	Vertical	0.049	0.020	0.369	0.079	5.06
7.	**Ghansiali**	N 00 E (L)	0.073	0.031	1.124	0.094	5.45
	Lat: 30.42 N	N 90 E (T)	0.083	0.049	1.45	0.111	5.71
	Long: 78.65 E	Vertical	0.039	0.016	0.33	0.058	7.59
8.	**Uttarkashi**	N 72 E (L)	0.054	0.033	0.318	0.023	5.83
	Lat: 30.73 N	N 18 W (T)	0.064	0.034	0.499	0.032	6.23
	Long: 78.45 E	Vertical	0.023	0.009	0.073	0.016	3.39
9.	**Barkot**	N 10 E (L)	0.017	0.006	0.025	0.002	6.21
	Lat: 30.80 N	N 80 W (T)	0.023	0.015	0.052	0.003	6.22
	Long: 78.21 E	Vertical	0.019	0.009	0.028	0.001	7.69
10.	**Almora**	N 53 W (L)	0.027	0.013	0.117	0.016	4.21
	Lat: 29.58 N	N 37 E (T)	0.028	0.019	0.085	0.011	4.32
	Long: 79.65 E	Vertical	0.027	0.018	0.088	0.007	5.43
11.	**Lansdowne**	N 70 E (L)	0.005	0.002	0.003	0.00014	6.69
	Lat: 29.83 N	N 20 W (T)	0.006	0.002	0.004	0.00013	8.49
	Long: 78.70 E	Vertical	0.011	0.003	0.007	0.00030	7.75

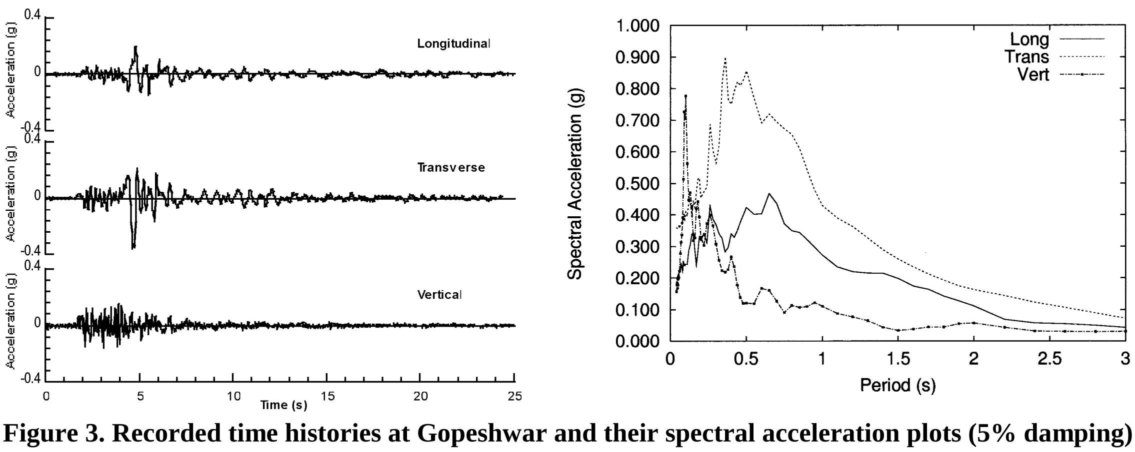


Figure 3. Recorded time histories at Gopeshwar and their spectral acceleration plots (5% damping)

The characteristic frequency of these motions, as measured by the mean rate of zero upcrossing, shows considerable fluctuations indicating the influence of local geology and topography. In particular, the ground motion at Gopeshwar, situated near the valley, is unusually rich in low frequencies for the near field motions and energy is concentrated in a narrow band. On the other hand the ground motion recorded at Okhimath, situated on the hilltop, is rich in high frequencies. Figure 3 shows the time history of recorded motion at Gopeshwar, the nearest station from the epicenter. It may be noted that although the high value of PGA (-0.359g) corresponds to a stray peak, its effective peak acceleration (EPA) is not much different from the recorded PGA. The EPA is defined as the peak value of the truncated ground acceleration record for which the spectrum intensity is 90% of that computed for the original time history [Watabe & Tohdo 1979]. Moreover, its energy is concentrated in the period range (0.1-2.5 s) used in the computation of spectrum intensity as shown in the spectral acceleration plots for 5% damping (Figure 3). The earthquake destructiveness potential factor P_D is commonly used for comparing the severity of ground shaking which simultaneously accounts for the effect of maximum amplitude, duration and frequency content of strong motion and is defined as $P_D = I_A \big/ \mu_0^2$ where I_A is Arias intensity and μ_0 is the mean rate of zero-crossing [Araya & Saragoni 1984]. The effect of rapid attenuation of ground motion is also reflected in values of P_D as shown in Table 1.

PERFORMANCE OF STRUCTURES

The region affected by the Chamoli earthquake is mountainous terrain where human settlement is dense in river valleys and sparse on hill slopes. Rising population has been responsible for new settlements on hill slopes, which were once considered unsafe. Major civil engineering projects in the area are: highways, bridges, small dams and micro hydroelectric projects and a few multi-storeyed RC framed buildings. Majority of residential buildings are box type, load bearing stone masonry which suffered extensive damage whereas RC framed (with infills) types have performed extremely well, even in the regions of high shaking. The seismic performance of load bearing masonry structures depend heavily on the strength, stiffness and ductility of surrounding walls to resist in-plane and out-of-plane inertia forces and the ability of diaphragms (floors & roofs) which distribute the forces to walls and maintain the overall integrity of the structure. The seismic performance of various types of material and construction techniques prevalent in the affected regions are described below:

Stone Masonry Buildings

In general, unreinforced stone masonry is very durable even in the hostile environment and has accommodated movements without becoming unstable and falling apart. However, some forms of stone masonry construction are extremely vulnerable to earthquakes. In Garhwal area, traditionally the stone masonry is laid in mud (clay) mortar and a “course” is comprised of large sizes of stone blocks sandwiched between many layers of thin wafers (2 to 5 mm thick) of slates (Figure 4a). These thin wafers of slate are filled in the undulating contours of large stones to create an “even” course and finished exterior surfaces as shown in Figure 4b. The resulting stone masonry is different from typical random rubble (R/R) masonry. The wall thickness can vary from about 450 to 750 mm consisting of two wythes each of 200 to 300 mm 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 frequently used to bind both wythes.

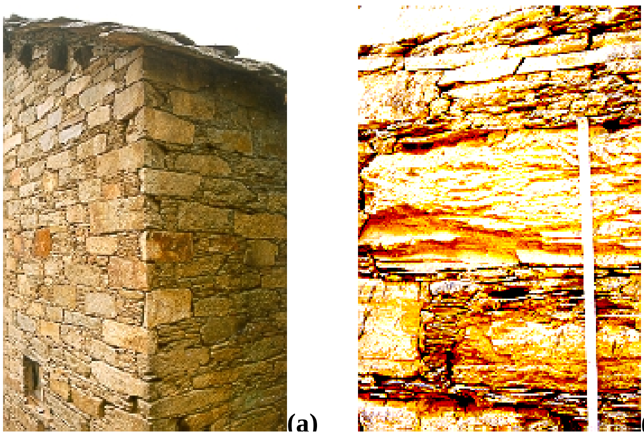

(a) (b)

Figure 4. (a)Traditional stone and slate masonry wall and (b) a close-up view of stone boulder and thin layers of slates


(c)

Figure 5. R/R masonry plastered & decorated to give an impression of dressed stone masonry

The damage to such masonry has been moderate to less depending on the quality of masonry and workmanship. Many layers of jointing material provide relatively large area for accommodating relative movements between masonry units (stone boulders and large number of thin slates) during the ground shaking thus, dissipating energy through friction and material hysteresis. 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 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 has undressed stones arranged in two wythes to give a total wall thickness varying from 450 to 750 mm. Stones are laid in mud mortar and exterior surfaces are often plastered in cement-sand mortar which can be “decorated” to give a false impression of dressed stone masonry (Figure 5). Old government buildings, hospitals, schools, jails, etc., built in R/R masonry suffered heavy damage. The stone masonry walls which did not have throughstones to hold the both wythes together failed by splitting along the length of the wall jeopardizing its vertical load carrying capacity. Such out-of-plane failures arising from the dynamic instability of tall unsupported walls are evident in the collapse of gable end wall (Figure 6a). In a number of cases this deficiency has caused separation of wythes leading to partial collapse of the wall (Figure 6b). This deficiency of R/R stone masonry was responsible for majority of the observed damage in the affected areas. In-plane shear failures were also observed of solid (Figure 5) as well as perforated walls (Figure 6c).

Figure 6. Failures of R/R masonry walls (a) Gable ends and cross walls (b) Separation of wythes and (c) In-plane shear failure of newly built wall weakened by openings.

Brick and Block Masonry Buildings

The usage of burnt clay brick masonry is a recent phenomenon in hilly areas and appears to be encouraged by Uttarkashi (1991) and Latur (1993) earthquakes where collapsed stone masonry walls were responsible for large number of deaths. Bricks are generally laid in cement-sand mortar and walls are often provided with lintel and roof bands and RC slabs (Figure 7a). In general, clay bricks are weak compared to stones and shear failure of brick walls was noticed with familiar X or diagonal cracks (Figure 7b). In addition to clay bricks, concrete blocks are recently being used a replacement for stone masonry (Figure 7c). Many factors have contributed to its growing usage such as unavailability of new quarries, time consuming and labour intensive stone masonry construction, uneconomical due to larger 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, crushed stone in various sizes with typical dimension being 300 mm x 225 mm x 150 mm. Very minor damage to such masonry walls was observed.

Figure 7. Brick & block masonry (a) brick house built with lintel bands (b) In-plane shear failure of brick masonry wall and (c) Concrete block masonry construction

Building Diaphragms

Pitched roofs and its variants have been the most popular choice for roofing in the region which have performed with varying degree of success. In rural areas, the roofs are either composed of simple wooden trusses or a frame work of wooden logs (Figures 8a & 8b). In government buildings, either timber trusses (Figure 6b) or joists (Figure 8c) along with wooden planks are generally used to support the roofing material. Galvanized corrugated iron (GCI) sheets are widely used roofing material for cheaply built school and government buildings, whereas slates are common for low cost dwellings. These roofs are inherently weak in shear and can not tie the walls together to provide the necessary “box action” for seismic resistance. Moreover, they are flexible resulting in deflections so excessive that walls are pushed out-of-plane Slate roofs are heavy attracting large inertia forces and slates can be easily dislodged causing a falling hazard. Most of roof failures can be attributed to either loss of support of roof trusses and joists or collapse of roof truss itself due to failure of joints and/or truss members

(Figure 9). Flat RC 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, lack of positive connection between the slab and wall diminishes the beneficial effect of rigid diaphragms in enhancing the overall structural integrity.

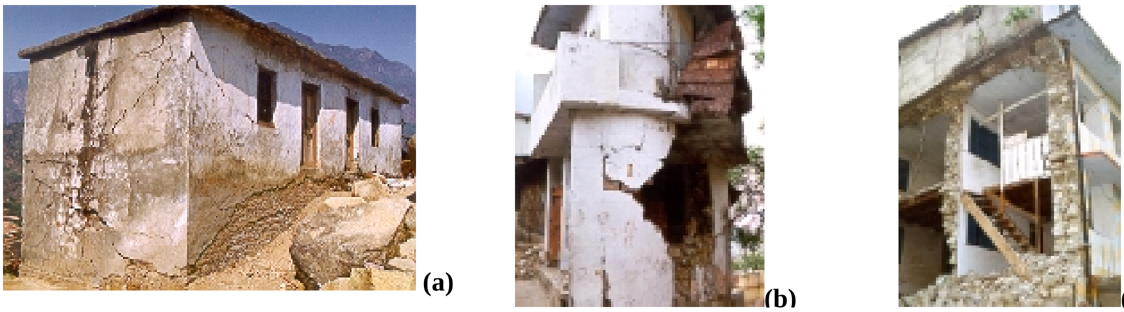
(a) (b (c)

Figure 8. Typical roof construction (a) Vertical post supporting ridge rafter (b) Framework of wooden logs & twigs and (c) Wooden joist and plank system

Figure 9. Collapse of roof structures (a) wall supporting the roof collapsed (b) partial collapse of double pitched roof truss and (c) collapse of wall supporting the roof truss

Building Configuration

Configuration-induced failures arising from substantial plan and vertical irregularities have also been observed with masonry structures. The most common configuration problems were: overstress resulting from torsional effects, accumulated damage in lower storeys of houses on slopes (Figure 10a), non-parallel vertical systems for corner buildings (Figure 10b), incompatible distortions at reentrant corners, and pounding, etc. 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 (Figure 10c).



(a) (b) (c)

Figure 14. (a) Vertical irregularity of hill-slope house (b) Non-parallel walls for a corner house and (c) Lack of connection between wall and floor and between exterior and cross walls

Roads and Bridges

The affected 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. Most of pedestrian bridges were of suspension types and no particular damage to the bridge structure or to the supporting pylons was noticed. Fissures on roads were noticed at places which were primarily due to the ground movement caused by unstable slopes.

CONCLUSIONS

A moderate earthquake, 6.8 on Richter scale, in Garhwal Himalayas rocked the cities of Chamoli, Gopeswhar and Rudraprayg, claiming about 100 lives and rendering 100,000 homeless. The epicenter was located near Gopeshwar and the maximum intensity on MSK scale was VIII-. The field survey indicates strong influence of lateral homogeneity of underlying rocks and topography of the area on the extent and severity of the damage. Furthermore, the elongation and orientation of isoseismals indicate that the rupture may have occurred on a low angle fault in WSW-ENE direction in the MCT zone. Analysis of strong motion records from eleven stations indicate that the ground motion attenuated very rapidly which can be attributed to the presence of highly fissured rocks. This observation is consistent with the observed intensity of shaking. Also motions in the epicentral region are relatively rich in low frequencies indicating a deep focus event. The structural deficiencies of prevailing construction types led to 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 affected area.

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