Some observations of the Chamoli earthquake-induced damage using ground and satellite data

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The havoc caused by the Chamoli earthquake of 29 March 1999 in the Alaknanda–Mandakini river valley region of Garhwal Himalaya was surveyed extensively and systematically, both in the field and from satellite data. The aim was to identify plausible patterns in the damage, so that observational constraints, useful for enhanced understanding of the earthquake and its related processes, could be established. This study provides evidences and constraints for reliable identification of (i) the mesoseismal zone of the earthquake, (ii) the possible up-dip and down-dip sections of the causative fault, (iii) the hypocentral zone, (iv) the fault plane and faulting mechanism, and (v) the possible geological causes responsible for induced landslides to occur mainly on the southern slopes of the mountains.

The Himalaya is one of the most unstable and seismically active mountain ranges of the world. With fairly frequent occurrences of damaging earthquakes and landslides all along its arcuate ranges, it demarcates a zone of intense natural hazards and seismic risk. In this century alone, heavy damage to human life and property has been caused here by three great earthquakes, viz. the Kangra earthquake (1905), Bihar–Nepal earthquake (1934), and the Assam earthquake (1950) as well as several moderate earthquakes, e.g. the Kinnaur earthquake (1975), Dharamshala earthquake (1986), Uttarkashi earthquake (1991) and the most recent earthquake of 29 March 1999, generally referred to as the Chamoli earthquake. Such earthquake-related casualties are due to the cumulative effect of the intensity of ground movement, the vulnerability of slopes to landslides, reactivation of former landslides, etc.1,2

In recent times, monitoring of small and micro earthquake activity along different sections of the Himalaya has led to the identification of several active fault zones3-9. Neotectonic activity along these faults results in contemporary morphological adjustments. Such regular and continuous earthquake activity induces a variety of mass wasting processes, e.g. landslides, rock falls, slump, etc., causing heavy loss to human lives, settlements and landscape. Spatial characteristics of the ground and human factors are also responsible for the vulnerability of the region to earthquake-induced hazards10.

The Chamoli earthquake of 29 March 1999, at 00:35 h local time rocked several parts of northern India with moderate to severe intensity causing considerable damage to human life and property, especially in the Garhwal Himalaya. According to available reports, more than 150 people were killed, 500 were injured and 2500 houses were damaged resulting in the loss of millions of rupees. Almost every house in the Garhwal region developed cracks. Human misery was further increased by disruption of communication links, damage to transportation routes and delayed arrival of supplies and rehabilitation measures. Numerous landslides, new and reactivated, were triggered by this earthquake with ground damages most severe on the loose terrace deposits being used for agriculture and settlement11.

Based on preliminary reports made available by US Geological Survey (USGS) on the Internet, this moderate magnitude earthquake ($M_s = 6.3, M_L = 6.6, M_w = 6.4, M_o = 5.2 \times 10^{18}$) was located at 30.49°N, 79.29°E at 12 km depth (Figure 1). Details of the fault plane solution provided by USGS identified the two nodal planes (NP1 and NP2) as NP1: strike = 282°, dip = 9°, slip = 95°; NP2: strike = 97°, dip = 81°, slip = 89°. From regional geological considerations, NP1 appears preferable as the fault plane of the earthquake.

Soon after the earthquake an extensive ground survey of the affected area was made, between 1 and 5 April 1999, by a three-member team from the Department of Earth Sciences, University of Roorkee, to assess the damage caused to human life and property to the mountain slopes. Also, simultaneously IRS-1C-PAN pre- and post-earthquake data sets (acquired from National Remote Sensing Agency (NRSA), Govt. of India, Hyderabad) were analysed to supplement the ground survey data especially for the higher, inaccessible mountainous regions. Using a pseudo colour transform (PCT) technique12,13 on these satellite data, ground damage and landslide occurrence due to the Chamoli earthquake could be identified accurately and assessed qualitatively.

In this article, we report integrated results available from this field and satellite survey of the earthquake-related damages and later provide possible geodynamical interpretations for these observations.

The earthquake-related damage to human life and property and to the mountain slopes was surveyed on the ground continuously along four distinct sections, forming a closed loop which straddled the Alaknanda and Mandakini river valleys. The sections were (i) in the Alaknanda river valley from Srinagar to Chamoli via Nandprayag; (ii) in the Alaknanda–Birahi Ganga river valley, from Chamoli to Pipalkoti; (iii) in the Balasuti–Senduna river valley from Chamoli to Mandal via Gopeshwar, Sagar, Gwar, Dewaldhar, Mawana and Viragan; and (iv) in the Mandakini river valley, from Mandal to Srinagar via Ukhimath (Figures 1 and 2).

Since accessibility by road to many affected regions, especially in the higher mountains, was particularly poor just after the earthquake, only a limited number of the
Figure 1. Location map of the study area. Location of Figure 3 is also identified here.

Figure 2. Isoseismal map of the Chamoli earthquake-affected area prepared from the ground survey undertaken between 1 and 5 April 1999.
numerous landslides triggered by this earthquake could be well surveyed during the ground investigations. Fortunately, satellite data for 26 and 31 March 1999 were available (acquired from NRSA, Hyderabad). These provided a synoptic view of the terrain, making it possible to study all landslides occurring over a larger area than would be possible from the field-based investigations alone. Further, the pre- and post-earthquake IRS-1C-PAN data allowed reliable differentiation between the newly triggered and the reactivated landslides (Figures 3–5).

These remote sensing digital data sets (Table 1) were processed to study the earthquake-induced changes in the following manner. Digital image processing of these data sets was performed mainly in MGE Advance Imager. Two graphical packages (Corel Draw 8.0 and Photo Styler 2.0) were employed during the preparation of final figures.

Generally, in the PCT technique various bands in different colour schemes, such as RGB, IHS and CMY are combined. However, a different approach has been adopted in the present study. This technique, developed to assess earthquake-induced landslides using remote sensing data, is cost-effective, unbiased, free from subjectivity, time-saving and provides qualitative and quantitative damage assessment. Both pre- and post-Chamoli earthquake IRS-PAN scenes were georeferenced using image-to-image rectification technique. Since IRS-PAN sensor provides only one-band information, the post-earthquake scene was kept in the red channel while the pre-earthquake scene was kept in green and blue channels. This provided a change index, whereby in terms of reflectance between the two dates, red colour depicted positive changes, blue and green colours depicted negative changes and black and white colours depicted no changes (Figures 3–5).

The major points that emerge from an integrated examination of the field and satellite data are the following: (1) Damage was most extensive in the Alaknanda river valley region. It became systematically more pronounced as one proceeded along the Alaknanda river valley from Srinagar towards Chamoli, Pipalkoti and Mandal and reduced as one entered into the Mandakini river valley from Mandal via Ukhimath. (2) Numerous landslides of

Figure 3. IRS-1C-PAN post-earthquake image of 31 March 1999, illustrating location of the various landslides induced by the Chamoli earthquake. Locations of Figures 4 and 5 are also identified here. The two major NE-SW directed mountain ridges exhibit dense forest on its NW facing slopes and terrace farming activities on its S and SE facing slopes. Most of the earthquake-induced movements (identified by white fan-shaped patches) have occurred on the S and SE orientated mountain slopes.
varying sizes, induced or reactivated by the earthquake were observed in the Alaknanda river valley region. Landslide occurrences were especially high along the Chamoli–Pipalkoti and Chamoli–Mandal sections. (3) The IRS-1C-PAN post-earthquake image of 31 March 1999 could identify locations of various landslides induced by the earthquake (Figures 3–5). Two major NE-SW directed ridges show that while the NW facing slopes are densely forested, the S and SE facing slopes are clear due to major terrace-farming activities (Figure 3). Further, as can be observed from the fan-shaped white patches in these figures, the earthquake-induced movements occurred

Figure 4. a, Pre-earthquake IRS-1C-PAN image of 26 March 1999. The small white areas depict existing landslides/rock falls; b, Post-earthquake IRS-1C-PAN image of 31 March 1999. Two major new landslides triggered by the Chamoli earthquake are distinctly visible; c, PCT image of the area identified in a and b. Red-coloured areas identify the Chamoli earthquake-induced landslides and other ground changes; d, Masked image of c. The two major landslides affecting approximately 0.075 km² area are also identified.
Figure 5.  

(a) Pre-earthquake IRS-1C-PAN image of 26 March 1999. The large area (to the south) and the smaller areas in white depict existing landslides/rock falls; (b) Post-earthquake IRS-1C-PAN image of 31 March 1999. A major new landslide (see centre of the image) triggered by the Chamoli earthquake is visible. Areas which were earlier affected by landslides have increased due to effects of ground shaking during the Chamoli earthquake; (c) PCT image of the areas identified in (a) and (b). Red-coloured areas identify the Chamoli earthquake-induced landslides and other ground changes; (d) Masked image of (c). The three major landslides affecting approximately 0.12 km² area are identified.
mainly on mountain slopes with S or SE orientation. (4) In terms of ground effects and building collapses leading to loss of human life and property, the maximum damage was confined to Chamoli and the zone to its north, over approximately 550 km² surface area. Within this region of peaked damage, less than 500 m north of Sagar (Figure 1), NNE of Chamoli, the surface trace of the MCT could be identified easily. (5) Some definite patterns amongst the perdition in this highly damaged zone could be identified: (i) Between Chamoli and Mawana (Figure 1), a small village situated about 4 km to its north, in the Balasutti-Senduna river valley, most buildings appeared to have collapsed due to major ground upliftment. (ii) In Mawana, situated in the MCT zone, 95% of the buildings had suffered total collapse, apparently due to such ground motion; for the remaining, all recently built with latest engineering specifications, the ground floors were severely damaged while the upper floors exhibited major horizontal displacement. Large, distinctly radial cracks in the ground were observed in Mawana. Amongst all villages and towns surveyed during this programme, the damage at Mawana was the most. (iii) At Gopenwar, about 2 km NW of Chamoli, a huge earthquake-induced landslide remained in action for several days. Similarly from Mawana one very large earthquake-induced and two small, reactivated landslides could be easily observed. (iv) North of Mawana, at Sagar, Gwar, Dewaldhar, Viragan, Badakoti and Mandal (Figure 1) very few buildings had collapsed totally. Here the damages implied major vertical overloading and weak horizontal shaking. (v) Prominent ground subsidence, some to the order of 10-15 cm, were noted at Sirokoma, immediately north of Mawana and also at Gwar, Dewaldhar, Viragan and Badakoti. (vi) Several instances of drying up of perennial streams as also moderate to excessive increase in flow in others were noted in this zone. (6) Figure 2 is the isoseismic map of the Chamoli earthquake prepared from the details of the ground survey of the earthquake-induced damage.

The isoseismic zone (Figure 2) has approximately 550 km² area and has been assigned intensity VIII of the modified Mercalli scale. These numerical values are commensurate with those of an earthquake having seismic moment $5.2 \times 10^{18} \text{Nm}$ (ref. 15) and ground acceleration 0.2 g approximately. Although there are obvious drawbacks in directly correlating intensity with ground acceleration, considering that in the Garhwal Himalaya the ground acceleration for the Uttarkashi earthquake of 20 October 1991 was instrumentally estimated to be 0.3 g (ref. 17), our observed estimate appears realistic.

Ghulaut et al. have estimated permanent horizontal and vertical ground displacements at different points of the ground lying vertically above and around a large rupture area caused by a shallow, gently dipping thrust along which slip varies only in dip direction. Their calculations indicate that the up-dip section of the ground immediately above the rupture zone is uplifted several times more than the surrounding region; in contrast, the down-dip section of the ground demonstrates considerable subsidence. On the basis of these theoretical results and the pattern of damage as observed in the isoseismic zone, it is inferred that the zone between Chamoli and Mawana possibly demarcates the up-dip section of the causative fault of the earthquake while the near total destruction at Mawana implies its termination. Similarly the prominent ground subsidence in the region north of Mawana possibly indicates the down-dip section of the fault. It has often been reported in the literature that near the epicentral zone, the vertical component of earthquake motion is far more prominent compared to its horizontal component. The pattern of damage to buildings at Gwar, Dewaldhar, Viragan, Badakoti and Mandal seems to

Table 1. Satellite remote sensing digital data sets (acquired from NRSA, Hyderabad) used in the present study

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Figure 6. Schematic representation of the USGS-based fault plane solution of the Chamoli earthquake of 29 March 1999.
indicate the proximity of these villages and towns to the epicentral zone compared to Pipalkoti, Chamoli or Mawana.

Further, large horizontal compression caused by shallow thrust faulting may result in intense release of pore waters from the highly fractured rocks. This possibly explains the presence of numerous new and reactivated streams with increased flow and also the drying up of already existing ones in the region.

According to USGS details of the chosen fault plane NP1, reverse thrust motion occurs on the causative fault dipping at a shallow angle (9°) along 12°N direction. During such a motion the rocks of the footwall would be displaced in a near-northerly direction, those of the hanging wall would be displaced in a near-southery direction (Figure 6). This should cause higher incidence of slope failures and sliding of rocks on the weak southern slopes of the mountains. This has indeed been evidenced in the satellite data examined in our study.

Results of investigation of the earthquake-related damage from ground and satellite data as reported in this study, provide observational constraints which lend support to the hypocentral location and fault plane solution as given by USGS.

Several geological and geophysical investigations have provided conflicting evidences both for an active MCT\textsuperscript{18,19} as well as for an inactive MC\textsuperscript{20,21}. This study indicates that the damage induced by the Chamoli earthquake is more pronounced nearer the MCT, rather than the MBT.

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ACKNOWLEDGEMENTS. We thank Prof. N. C. Nigam, Vice Chancellor and Prof. A. K. Awasthi, Head, Department of Earth Sciences, University of Roorkee for their encouragement and providing necessary funds to conduct this study. I.S. acknowledges the support provided by Prof. A. K. Pachauri and Dr. M. Israil, Department of Earth Sciences and Mr. Umakant Pawan, District Magistrate, Chamoli.

Received 24 June 1999; revised accepted 26 October 1999

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New record of *Mytilus viridis* Linn., its density, growth and accumulation of heavy metals on Saurashtra coast, Arabian Sea

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The occurrence of green mussel *Mytilus viridis* was recorded for the first time in the Gujarat coast. The assessment of mussel density, growth and biomagnification of heavy metals from its natural beds were performed from September 1998 to June 1999. The mussel density was maximum both in number and biomass at low tide level and minimum at high tide level. The specific growth rate of mussel was 13.25 (length), 31.16 (total weight) and 3.38% per month (meat weight) during the study period. Data regarding accumulation of heavy metals reflected that the metal load was increased with increasing mussel size and the peak values were observed at an average size of 6.21 mm. The mean concentration of Cu, Fe, Pb, Cd, Zn, Co, Mn and Hg were 3.91, 9.40, 20.10, 1.53, 37.34, 67.35, 1.01 μg g\(^{-1}\) dry wt and non-detectable, respectively. Since the mussel showed considerable biomagnification of heavy metals, it can be used for marine pollution monitoring.

The green mussel *Mytilus viridis* (Syn. *Petra viridis*) is an important food for the people of southern India. It supports substantial fishery of some consequence along the coast of Karnataka and Kerala. Though green mussels

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