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ORIGINAL PAPER

Landslide Hazard in the Nainital township, Kumaun Himalaya, India: the case of September 2014 Balia Nala landslide

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Abstract Nainital township located in the Kumaun Lesser Himalaya is known to be vulnerable to landslides since past, and it has been reported that half of the area of the township is covered with debris generated by landslide. A disastrous landslide in the Rais Hotel locality on the right side of the Balia Nala struck during September 2014 after the excessive rainfall. Geologically, the area dominantly comprises limestone with shale and slate which are highly crushed and weathered due to the presence of the Nainital Lake Fault that extends into Balia Nala as Balia Nala Fault. Ground-penetrating radar study depicts that these rocks are overlain by thin debris cover of the order of 5–10 m. The geotechnical studies confirm these rocks and the overlying soil as having very low strength. The landslide has triggered because of the excessive rainfall in the area. It has been observed that rainfall in the area has increased since 2010. An increase in more than 100 % intensity of rainfall during the monsoon from an average 33 mm per day (1995–2013) to 68 mm per day in 2014 is the main triggering factor for the initiation of landslide. The area has been continuously monitored for the last more than 3 years, as the distress in the area has been reported in the form of development of cracks. In order to prevent further sliding, immediate measures have to be taken to channelise water on both sides of the hill slopes so that the ingress of water into the slope is minimum.

Keywords Landslide · Rais Hotel colony · Balia Nala · Nainital · Kumaun Himalaya · India

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1 Introduction

Landslide is a complex dynamic system and is a part of the normal geomorphic cycle. It is common in the mountainous region, particularly in the Himalayan terrain, and poses a serious threat when it interferes with any human development. Some of these landslides have been reported and studied particularly when these interfere with human developmental programme (Sah and Bist 1998; Bist and Sah 1999; Paul et al. 2000; Bhasin et al. 2002; Naithani et al. 2002; Sah et al. 2003; Gupta and Bist 2004; Gupta and Ahmed 2007; Gupta and Sah 2008; Rana et al. 2012; Gupta et al. 2013); however, there are many landslides that go unreported as these occur in isolation and away from human habitation. An individual "landslide" characteristically involves many different processes, operating together, often with differing intensity during successive years. A landslide that had struck on 12 September 2014 in Rais Hotel colony locality in the Nainital township is a recent example which is being monitored for the past few years.

The present study gives an engineering geological description of the area based on the geotechnical investigations performed in the past few years. Such investigations attempt to

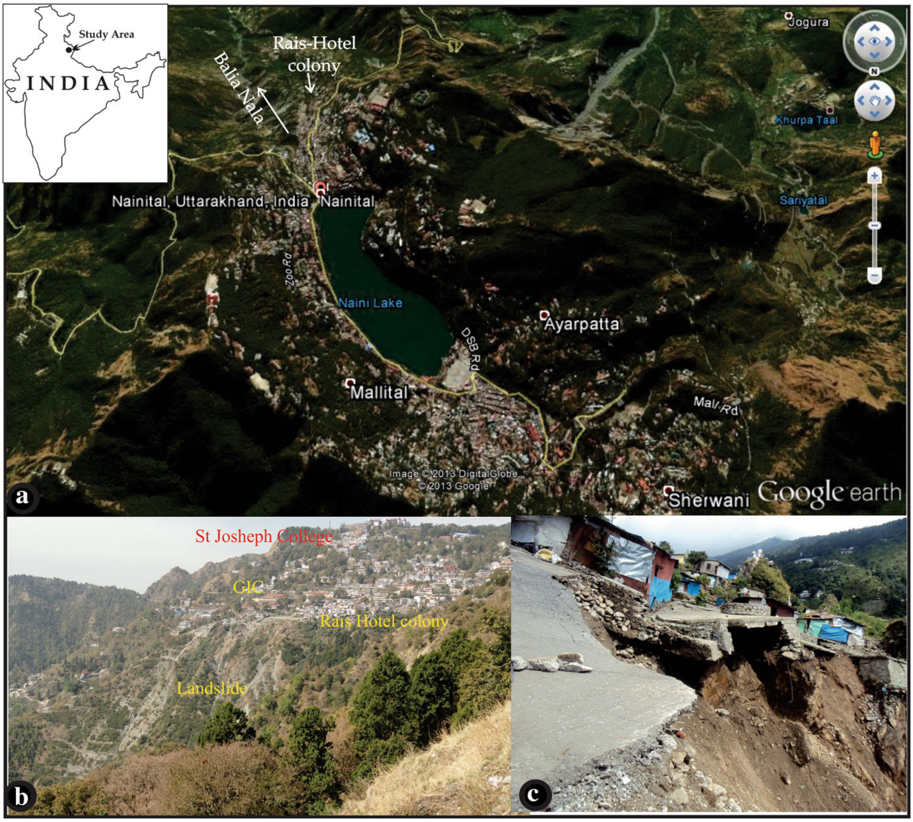

Fig. 1 Location map of the area, **a** Google earth image of the study area and its surroundings. Note the location of the Balia Nala and the Rais Hotel colony locality towards the southern end of the Nainital Lake, **b** view of the Rais Hotel colony along with flat playground, Government Inter College (GIC) and St Stephen's College and **c** concrete footpath descending the slope that joins GIC and the Krishnapur located at the base of the slope

interpret the processes responsible for the failure of slope and to infer the environmental conditions for the operation of such processes. However, it has been recognised that there are limitless opportunities to go astray twist the failure and its interpretation. The site has been investigated to understand various factors that led to the slope failure along the right side of the Balia Nala and its possible consequences in future.

2 Study area

The study area is situated at the Rais Hotel colony locality in Nainital township and is located at 29°22′27″N and 79°27′56″E, at an elevation of about 1872 m. It is situated on the south-east-facing slope on the right bank of the Balia Nala that originates from the south-eastern extremity of the Nainital lake (Fig. 1a). The locality, constituting about 60–70 houses, is located at an elevation ranging between 1850 and 1875 m (Fig. 1b). A flat playground measuring about 60 m × 40 m is located on the slope. Further upslope of the

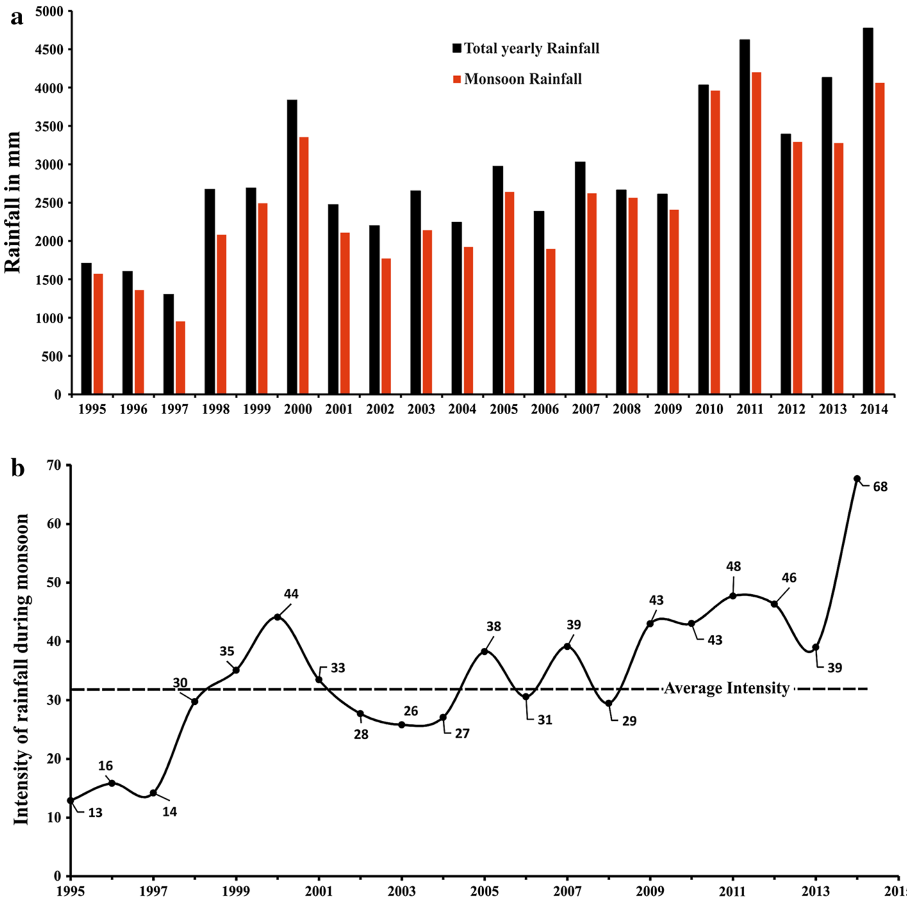

Fig. 2 **a** Average annual rainfall totals for the year 1995–2014 along with the rainfall during the monsoon period, i.e. during June–September and **b** intensity (total rainfall/number of rainy days) of rainfall during 1995–2014 for the monsoon period

locality lies the Government Inter College (1905 m), Nainital–Haldwani Road (1915 m), Government Girls Inter College (1940 m) and St Joseph College at the top of the ridge (2085 m). A concrete footpath connecting GIC–Krishnapur passes near the Rais Hotel colony descends the slope (Fig. 1c).

The region has tropical climate with pleasant summers and cold winters. Average summer temperature is around 25 °C, and the winter temperature drops to about 0 °C. During winter, the township often experiences snowfall. The average yearly precipitation recoded during 1995–2009 is about 2468 mm, whereas it is 4190 mm during 2009–2014, thus recoding an increase of about 70 %. The rainfall during the monsoon period, i.e. between June and September, records more than 75 % of the yearly rainfall (Fig. 2a).

Figure 2b depicts the intensity of rainfall (total rainfall divided by the number of rainy days) during the monsoon. It has risen from 30 mm per day (during 1995–2009) to 49 mm per day (during 2010–2014). It has also been noted that during 2014, the year of the occurrence of the landslide, the area experienced extraordinary high rainfall intensity of 68 mm per day (Fig. 2b).

3 General physiographic set-up of the area

Nainital township and its environs dominantly constitute limestone, shale and slate rocks belonging to the Blaini, Krol and Tal formations of the Lesser Himalaya (Fig. 3). The detailed account of the geological set-up of the area was given as early as by Middlemiss

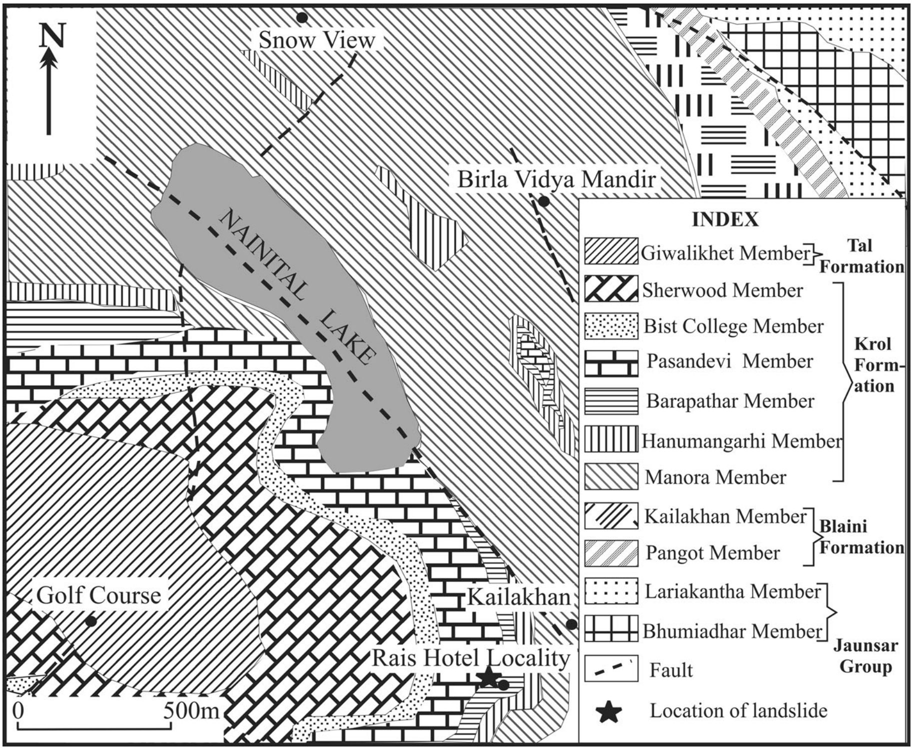

Fig. 3 Geological map of the Nainital township and its environs

(1890). Subsequently, numerous workers contributed towards understanding the geological and structural set-up of the area (Holland 1897, Heim and Gansser 1939, Auden 1942, Nautiyal 1949, Hukku and Jaitely 1964, Valdiya 1988, Sharma 1998 and Jiang et al. 2002). The characteristic features of each formation present in the area are briefly discussed hereunder:-

3.1 Blaini formation

Blaini formation, present dominantly mainly in the north-eastern and eastern parts of the Nainital lake, mainly comprises conglomerates, associated with purple slate, quartzitic and dolomitic limestone. It is divisible into Pangot Member and Kailakhan Member. Pangot Member is mainly dominated by conglomerate and limestone, whereas the Kailakhan Member, also referred as Infra-Krols, is dominated by carbonaceous slates interbedded with shale.

3.2 Krol group

The greater part of Nainital township is made up of Krol group of rocks. Krol group mainly comprises argillaceous limestone, grey and blue dolomitic limestone, dolomite and tuffaceous limestone including red and purple ferrugineous shale, different coloured calcareous slate, greywacke, siltstone and fine-grained muddy sandstone. Broadly, there are four recognisable lithounits, viz. (1) shale and slate, (2) limestone, (3) tuffaceous limestone and (4) sandstone within this group. This group has been divided into different members, namely (1) Manora Member, (2) Hanumangarhi Member, (3) Barapathar Member, (4) Pashandevi Member, (5) Bist College member and (6) Sherwood Member (Valdiya 1988).

3.3 Tal formation

Tal Formation is represented by pyritic shale and slate with stromatolitic limestone interbedded with brownish to muddy, fine-grained sandstone and siltstone. It is best developed around south-western side of the Nainital Lake.

The slopes around the Rais Hotel colony locality is dominantly occupied by limestone and calc slate having phyllitic texture belonging to Barapathar Member of the Krol formation (Fig. 3). These slopes are covered with thin veneer of sediments. These rocks are highly weathered and jointed and dip at moderate angle of 35° towards variable direction, i.e. from WSW to NE direction. Two prominent sets of joints trending NNW–SSE dipping at an angle of 50° towards ENE- and E–W-trending vertical joint have been noted in the area besides the presence of random joint trending NW–SE and dipping at an angle of about 35° towards NE.

A number of folds, faults and thrusts traverse through the area. A NW–SE-trending Nainital Fault, also referred as Lake Fault (Valdiya 1988), traverses through the Nainital Lake. The fault extends towards the south-eastern end of the lake and follows the Balia Nala, and here it is referred as Balia Nala Fault. There are numerous offshoots from this fault, the signatures of which have been observed in the Birla Vidya Mandir School, Kailakhan area and the Snow view locality (Fig. 3). The rocks in the area highly folded. The presence of numerous folds and faults in the area has made the rocks highly crushed.

Geomorphologically, the area surrounding Nainital lake is occupied by several ridges, and the ground elevation is variable between 1694 and 2611 m above msl. Prominent ridges in the area run NW–SE parallel to the Nainital lake. Small E–W-trending ridges have also been observed. Naini peak is the highest peak in the area with an elevation of about 2611 m above msl. Sher ka Danda (2402 m), Deopatha (2435 m) and Ayarpatha (2352 m) are the other major peaks surrounding the area. Nainital lake is located at an elevation of about 1935 m and is the main feeder for the Balia Nala that flows towards SSE. The Balia Nala that follows the fault, termed as Balia Nala Fault, has carved a linear valley. It is characterised by deep, narrow valley with steep slopes and high channel gradient. The Nala is observed to undergo a rapid downcutting and have rocky channel with channel material comprising mostly of debris and fine sediments.

4 Past history and Rais Hotel colony landslide characteristics

Nainital and its surrounding regions are known to be vulnerable to landslides and related mass movement activities since past. Valdiya (1988) noted that about half of the area of the Nainital lake basin is covered with debris generated by mass movements. In the living memory of human being, the landslides in the Nainital township date back to 1867 and 1880 when Naini peak-Sher ka Danda spur failed. However, first record of landslides on the right side of Balia Nala dates back to 17 August 1898 following 102 cm of incessant rainfall for 8 days (Middlemiss 1898). The slide surged across the valley damaging the right bank as well, and since then, both sides of the Balia Nala are continually and uncontrollably ravaged by landslides and related mass movement activities. The landslides along both sides of the Nala are progressively expanding since then. A major landslide along the right bank of the Balia Nala occurred in 1972. Subsequently, the eastern slopes at the lower elevation of the Balia Nala are continuously sliding, particularly due to toe erosion.

A landslide had occurred on 10 September 2014 in the Rais Hotel colony locality after the continuous rainfall. The slide had damaged about 20 m stretch of the concrete footpath connecting GIC–Krishnapur and washed away about 360 m^2 retaining wall on the slope (Fig. 1c). Prior to the occurrence of landslide in the area, cracks in the houses and on the ground have been observed, clearly indicating that the slopes were moving slowly (Fig. 4).

Longitudinal profiles along the Balia Nala trending NNW–SSE indicate that the general channel gradient in the upper part near its origin from the Nainital Lake is about 25°

Fig. 4 **a** Cracks on the walls of the houses located adjacent to the GIC playground before the occurrence of September 2014 Rais Hotel colony landslide and **b** subsidence of the area and damage to the houses after the occurrence of September 2014 Rais Hotel colony landslide

(Fig. 5). A major knickpoint has been observed at an elevation of about 1500 m above msl, where the channel gradient drops to about 5°, which continues till 1400 m, and further downstream the channel gradient again increases to about 20°. The gentle gradient in the zone between 1400 and 1500 m above msl has been well correlated with a landslide that occurred on the left bank of slope in the Kailakhan region in 1898, depositing 5.5 million tons of debris into the Nala (Middlemiss 1898). Another small nickpoint in the profile has been observed at about 1770 m above msl. This is also related to the landslide along the Nala. The overall steep gradient of the Balia Nala is mainly because of the active movement of the Balia Nala Fault as has been evidenced by the continuous widening of cracks on the walls of the houses located on either sides of the Balia Nala (Fig. 6).

Figure 7 depicts the cross section along the Rais Hotel locality landslide that occurred on 12 September 2014. The crown of the landslide is located at 1872 m. The main scarp of the landslide is about 225 m high. The slide is located on a small spur, and the general hill slope is very steep with an angle of about 70° towards south-eastern side. The slide is being widened along both sides as well as progressing in the upward direction as indicated by the cracks on the slope and in the houses. The slide has partially damaged about 20 houses located in the vicinity and has endangered all the houses in the locality (Fig. 8a). Cracks have also been observed in the building of the Govt. Inter College, located on the crown portion of the landslide.

The entire slope in the landslide zone in the upper part is made up of weathered limestone and dolomitic limestone, whereas the lower slopes towards the Balia Nala are made up of black carbonaceous slate. The slates are highly weathered and leached with white and yellow encrustation. These are covered with thin veneer of debris constituting mainly pebble- and cobble-size limestone, sandstone and slate embedded in sand–silt–clay matrix (Fig. 8b). The rocks exposed in the landslide zone dip towards NE at an angle of about 35° (towards up-drainage direction). The slope towards the lower slope near the Balia Nala is being continuously eroded by the Nala and is thus very steep of the order of 80°–85°.

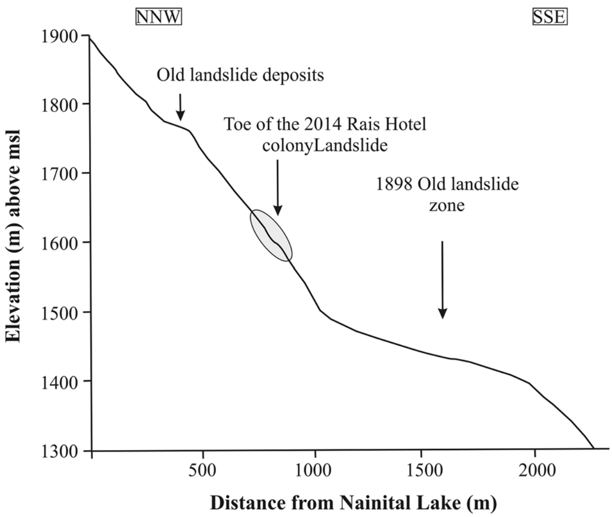

Fig. 5 Longitudinal profile along the Balia Nala indicating very steep channel gradient and old landslide deposits

Fig. 6 **a** Cracks surfaced again and in continuously widening on the retaining wall in a school building that was repaired in 2010 and **b** tiles of the floor have been uprooted in a zone of about 2 m width and more than 50 m length in the Kailakhan region on the left flank of the Balia Nala

Fig. 7 Cross section of the Rais Hotel colony landslide that struck in the Nainital township in September 2014

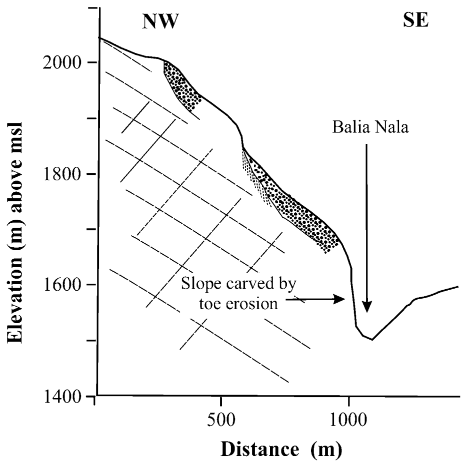

Fig. 8 **a** Panoramic view of the Rais Hotel colony landslide that has damaged about 20 houses and is endangering the entire Rais Hotel locality including the GIC, **b** main body of the landslide depicting weathered rocks in landslide zone and is covered with thin veneer of sediments

5 Geomechanical properties of rocks and soils

Geomechanical properties of rocks constituting the slope where Rais Hotel colony landslide had occurred have been estimated in the field by rebound (*R*-) value using N-type Schmidt Hammer, whereas for soil direct shear tests have been carried out in the laboratory. *R*-values have been calculated for limestone located upslope near the Rais Hotel colony locality, as well as for shale and slate located near the Balia Nala. All the outcrops in the area highly jointed and fractured and are closely spaced. It is customary to measure the *R*-value away from the fracture or joint; however, in the present case, since these joints and fractures were closely spaced, it was not possible to take *R*-value readings away from the fracture or joint; therefore, all the readings were taken near the discontinuities. A total of 50 Schmidt hammer rebound measurements were taken randomly at each site, following the methodology of Gupta (2009). All the measurements were taken with hammer held horizontally and at right angle to the surface. The *R*-value at the site is observed to be variable between 10 and 15 with an average value of 12 for limestone, and for shale and slate, it is variable between 14 and 35 with an average *R*-value of about 22. Based on the correlation between *R*-value and compressive strength of rocks, it has been suggested that the compressive strength of these rocks is less than 20 MPa. (Barton and Choubey 1977; Tandon and Gupta 2015).

Soil samples have been collected near the Rais Hotel colony locality and have been analysed for the cohesion and friction angle. A series of unconsolidated, undrained direct shear tests were performed. The tested samples were predominantly non-plastic, sandy silt. The samples were sheared under constant normal stress of 25, 50, 100, 200 and 400 kN/m^2. It has been observed that cohesion and friction angle are 1.95 kPa and 31°, respectively, indicating low strength of the soil.

6 Ground-penetrating radar (GPR) study

In order to estimate the depth of the overburden–bedrock interface, ground-penetrating radar (GPR) profiling has been carried out at number of locations. The survey setting used for the profiling is depicted in Table 1.

Ground-penetrating radar, an electromagnetic (EM) geophysical method, has been used for high-resolution detection and mapping the subsurface soils-rock conditions. The data are acquired by transmitting pulses of electromagnetic (EM) waves into the ground from a surface antenna, and the waves get reflected from bedrock/geological–structural features/bedding contacts and then are detected back at the ground surface with a receiving antenna. As the radar waves pass through various materials, the velocity of the waves changes

Table 1 Survey setting used for the GPR profiling in the area

GPR unit type	FieldFoxp
Antenna	100 MHz central frequency
Start frequency	20 MHz
Stop frequency	200 MHz
Spacing between antenna	0.5 to 0.75 m
Cables length	2 × 30 m
Survey mode	Auto
Data acquisition technique:	Profile off-setting

depending on the physical and electrical properties of the material through which they are travelling. Each time the radar pulse traverses a material with a differing composition or water saturation, the velocity changes and a part of the waves reflects off of the object or interface, while the rest of the waves pass through to the next interface. The reflected signals return to the antenna and are received by the digital control unit. The control unit registers the reflections against two-way travel time in nanoseconds and then amplifies the signals. The output signal voltage peaks are plotted on the GPR profile as different colour bands by the digital control unit.

In the present study, GPR Fieldfox unit with step frequency having frequency range between 2 MHz and 6 GHz was used. The survey was conducted using 100 MHz central frequency antenna of 1.2 m length that generally produces about 10–15 m depth of penetration depending upon the subsurface strata. The data were acquired by common offset profiling technique by placing transmitter and receiver antennas on the surface at 0.5–0.75 m distance apart. The radar signal is transmitted into the ground by the transmitter antenna, and the reflected signal that contains information about the subsurface strata was received by the receiver antenna, assuming that the wave speed in ground is 10 cm/ns. In the reflection profiles, measured two-way travel time to radar reflectors is displayed on the vertical axis, while the distance the antenna has travelled is displayed on the horizontal axis.

The survey has been carried out on the flat ground in the Rais Hotel colony locality located on the left flank of Balia Nala (29°22′27″N; 79°27′56″E, elevation 1872 m). GPR profiling was done at six transacts (Fig. 9) to measure the exact thickness of the overburden. These GPR profiles are depicted in Fig. 10. All the profiles indicate that the soil mass below the ground is highly disturbed and is probably debris from previous slides in the area. The depth of the disturbed mass varied between 2 and 10 m. It is estimated that the interface of the bedrock–overburden on the slope is located at about 2–5 m below the ground. This has also been corroborated with the numerous drill holes data carried out on the SSW-facing slope adjacent to the Nainital Lake for the construction of Nainital Ropeway (CBRI 1983).

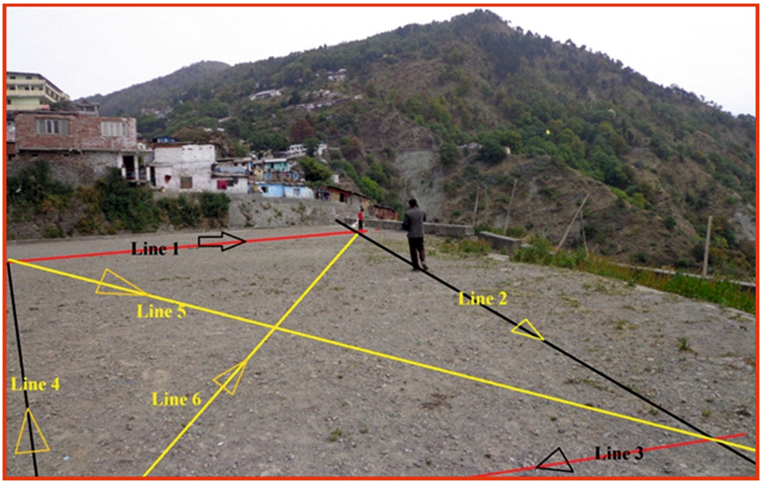

Fig. 9 Six transacts on the flat playground in the Rais Hotel colony where the GPR survey was carried out

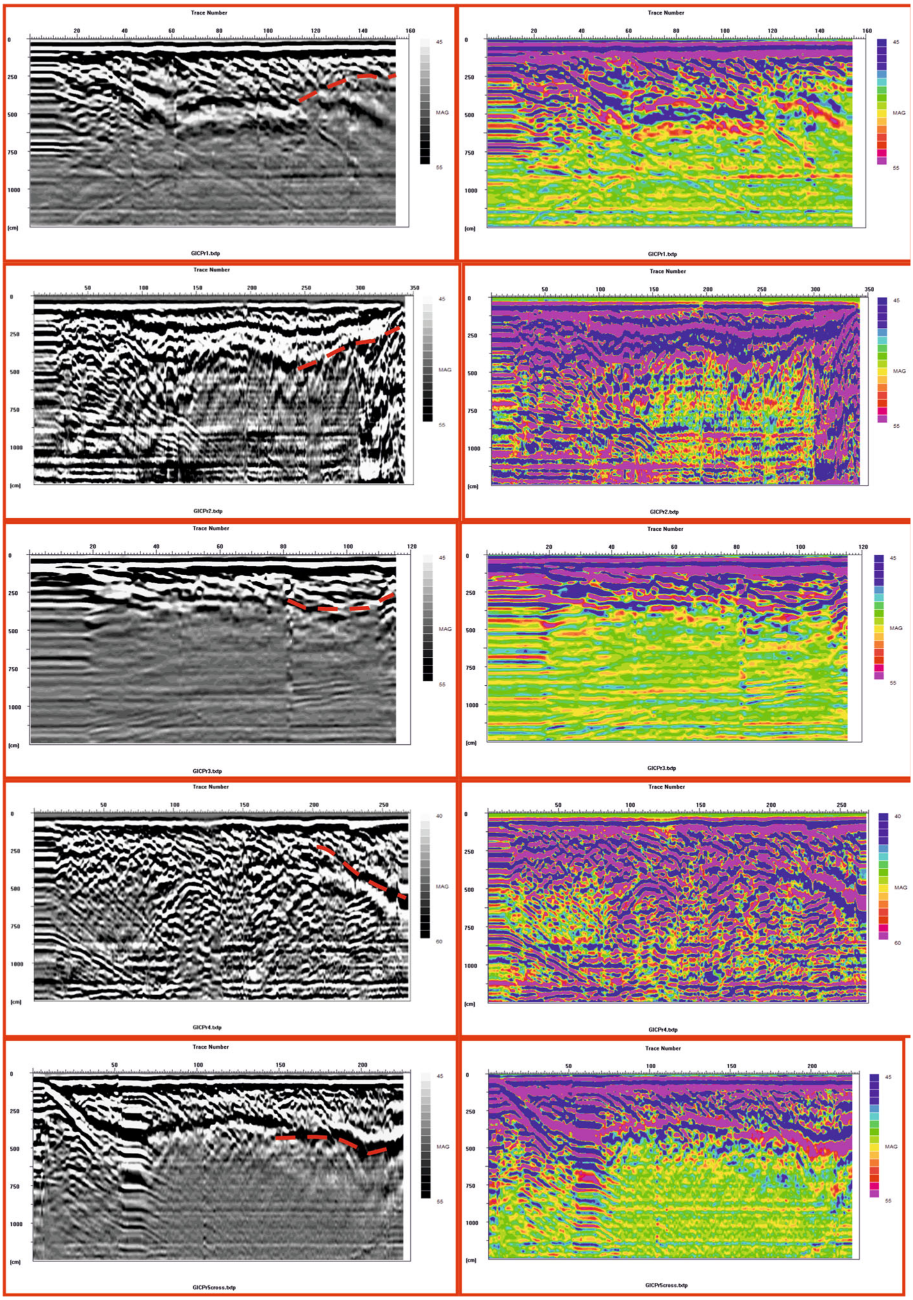

Fig. 10 GPR profiling along lines 1–6 on the Rais Hotel colony playground (refer to Fig. 9). *Red dotted line* indicates the interface of the rock and overburden

7 Discussion and conclusions

Nainital township is known to have the problem of landslides since past. The documented history of landslides in the township dates back to as early as 1867 when a portion of the hill slope failed. A major landslide in the township had also occurred in September 1880 on the Sher ka Danda ridge killing 151 persons. Again in 1898, a major landslide had occurred on the left bank of the Balia Nala, in the Kailakhan region, killing 28 people (DMMC 2011).

The main reasons for occurrence and higher probability of landslides in the area are the weak geological set-up, besides the presence of structural discontinuities. The greater part of the area is dominantly comprised of limestone and dolomitic limestone, which is characterised by highly jointed, fractured and micro-cracked and therefore exhibits very low unconfined compressive strength. Further, these rocks are traversed by a major NW–SE-trending Nainital Lake Fault which, towards the south-eastern extremity, is also referred as Balia Nala Fault, as here it follows the Balia Nala (Fig. 3). The offshoots from this fault have also been observed in other areas like in the Birla Vidya Mandir. The fault has also contributed towards shearing and weathering of the rocks in the area (Fig. 12). It has further been noted that slopes in the entire area are covered with thin veneer of Quaternary deposits. These deposits are highly disturbed as interpreted by GPR survey, and the thickness of these deposits is found to be shallow of the order of 2–10 m (Fig. 10). At many places, these deposits are highly unstable and vulnerable to sliding particularly during excessive rainfall or shaking during earthquake. Among these, the slopes around the Rais Hotel colony located by the side of the Balia Nala were adversely affected as the distress in the locality has been observed and cracks in the houses located in the area were

Fig. 11 Open cavities in the rock slope on the lower valley slope indicating that the slope may fail in future

Fig. 12 Highly sheared and weathered rocks on both sides of the Balia Nala due to the Nainital Fault, here referred to as Balia Nala Fault

noted to be widened with time (Fig. 4a). Further downhill on the slope, open cracks and cavities in the slope have been observed (Fig. 11), indicating the probability of future hazard. The area at the lower elevation is being monitored for its surface movement using GPS, and it has been observed that the area is sliding slowly at a rate varying between 10 and 60 cm/year (Kotlia et al. 2009). Cracks have also been noted on the left bank of Balia Nala in the Kailakhan area. These cracks were noted at different elevations, prominently at about 1898, 1929 and 1950 m above msl, running along ESE–WNW direction. This side of the Balia Nala is occupied by the army camp, and at the ridge top, Nainital Halipad is located. Thus, landslides at the lower elevation (Fig. 12) are posing serious threat to the Halipad and the army set up in the area.

Recently, with the observed shift in the rainfall climatic pattern (Gupta and Sah 2008) and the more extreme climatic conditions, as has been observed in June 2013 in the north-western Himalaya (IMD 2013), these slopes pose serious threat to the lives and properties in the region. Therefore, it is utmost important that all the slopes, in the present climatic scenario, must be evaluated and categorised for their hazard potential.

Summarising up, it has been concluded that slopes in and around Nainital township are geologically unstable. The instability has been observed particularly along both sides of the Balia Nala. The propensity for instability is mainly due to inherent geological and structural set-up of the area in the form of highly weathered rocks traversed by the Balia Nala Fault along with the presence of low-strength thin veneer of debris on slopes. This has further been corroborated with the numerous longitudinal wide open cracks on both sides of the Balia Nala. The situation has further been worsened as during 2000–2014 an increase in annual rainfall of about 70 % has been recorded (Fig. 2a).

It is therefore utmost important to take immediate preventing measures in the form of construction of proper drainage network on the slopes so that ingress of water into the slope is minimum.

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