J. Earth Syst. Sci. (2020)129 53
https://doi.org/10.1007/s12040-019-1327-y

Landslides assessment using geophysical and passive radon exhalation detection techniques in Murree Hills, northern Pakistan: Implication for environmental hazard assessment

Khawar Ashfaq Ahmed[1], Sarfraz Khan[4,*], Mahmood Sultan[3], Umair Bin Nisar[2], Muhammad Rizwan Mughal[1] and Shahid Nadeem Qureshi[1]

[1]*Comsats University Islamabad (CUI), Islamabad, Pakistan.*
[2]*Center for Climate Research and Development (CCRD), CUI, Islamabad, Pakistan.*
[3]*Center for Earthquake Studies, National Centre for Physics (NCP), Islamabad, Pakistan.*
[4]*National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, KP, Pakistan.*
**Corresponding author. e-mail: sarfraz_qau@yahoo.com*

MS received 5 September 2018; revised 11 September 2019; accepted 30 October 2019

Geophysical investigation of three landslides in Murree Hills was carried out using geophysical techniques (i.e., seismic refraction and electrical resistivity) and geochemical tool (passive radon exhalation detection method). The seismic data was acquired by using reverse shooting scheme employing placement of source after the last active geophone in the spread. The acquired data was analyzed, and layer velocities were estimated by using Hagedoorn's method. The resistivity data was modeled in terms of true resistivity of subsurface material by curve matching technique. The radon emission was determined as alpha track densities for each detector planted in dosimeter in the sub-surface along survey profiles. The results of all the methods employed were interpreted and correlated in the context of local geology, and also considering seasonal and anthropogenic factors. The study guides the importance of local geological structure and lithologies in the formation of thick weathering layer. The weathered layer wet/moistened through rains in the winter and summer seasons or daily use of water due to urbanization of the area, exerts more downslide force thus resulting landslides. This thickness of weathered layer is determined by using seismic refraction and resistivity methods for the three landslides (MIT, Kuldana and Chitta Mor) which is in agreement. Also, the passive radon exhalation detection technique (geochemical investigation) has delineated the stable and unstable areas within the three landslide zones. These geophysical and geochemical investigations are recommended on the major landslides of the area prior to damage control measures.

Keywords. Environmental disaster; seismic refraction; vertical electrical sounding; radon exhalation; landslides; Murree Hills.

1. Introduction

The surface of the earth is subjected to weathering and the gravity is constantly acting on every material on earth. This initiates the phenomena of mass movements which may be on the surface or near-surface that transport materials down slope side. Such mass movements are almost negligible on a day-to-day basis but can be sudden as in the shape landslide (Rafiq *et al.* 1989; Deoja *et al.* 1991;

Published online: 22 January 2020

Montogomery 1991; Schaffner 1998; Densmore and Hovius 2000; Farooq 2000; Abbasi *et al.* 2002; Bichler *et al.* 2004; Ibsen and Casagli 2004; Dunning *et al.* 2007; Sass *et al.* 2008; Hafeez *et al.* 2019). The term landslide is typically assigned for the displaced mass on the hill-slopes, larger the landslide greater will be the mass displacement.

Murree is an important transportation point and the base route for connecting Islamabad-Rawalpindi to the Kashmir valley. This road route at times badly affected by landslides, especially during the monsoon season (Abbasi *et al.* 2002). The road encircling Murree has a number of landslides and has induced major landslide hazards to the old town located upslope at the top of the ridge.

The objective of this study is to determine the possible causes of land sliding and mass movement in Murree Hills. An area was selected around the main town where major construction has undergone and been a focus of intense human activities since past two decades. For detailed investigations, three landslides encircling all around the Murree Town were focused, i.e., Chitta Mor landslide on northwestern slope, Kuldana landslide on northern slope, and MIT (Murree Improvement Trust Office) landslide on southeastern slope.

For geological investigation, radon exhalation monitoring method is applied to determine the difference in and around stable and unstable areas of the three selected landslides. Radon exhalation monitoring method has been used in the studies of different geological processes, i.e., earthquake prediction (Ulomov and Mavashev 1967; King 1978), monitoring of volcanic processes and eruption (Chirkov 1975), location of faults, and exploration of uranium deposits (Young 1956; Dyck 1972).

Two geophysical methods (i.e., seismic refraction and electrical resistivity) were also applied in the study area for geological investigation. Seismic method has been widely used for subsurface exploration (Bichler *et al.* 2004; Ranjan *et al.* 2015; Gupta *et al.* 2019). Electrical resistivity method is also among the important non-destructive geophysical methods (Bharti *et al.* 2019; Singh *et al.* 2019). The method helps in delineating the groundwater potential zones and to study the other geotechnical and environmental problems (Bharti *et al.* 2016a, b; Gupta *et al.* 2019).

The results of the study will provide an understanding to suggest ways and means for engineers to minimize the hazard by adopting remedial measures.

2. Geological settings

The town of Murree and surrounding vicinities are at the foothills of the western Himalayas (Sub-Himalayas). Landsliding and other mass movements in the area are result of lithologies with weak strength and intense soil and rock deformations (Neiderer and Schaffner 1989). The Murree and surrounding Hazara district region are characterized by a series of NE–SW trending ridges with a well-defined drainage pattern dominated by two major antecedent rivers, Jhelum and Indus (figure 1a).

The Murree town (quadrangle 33°54′15″–33°55′15″N and 73°23′–73°25′E) is a part of orogenic belt and deformed extensively due to mountain building processes (Gansser 1964). The study area is located approximately 50 km northeast of Islamabad with elevation of about 2200 m above sea level (asl). The Murree Thrust trending NE–SW is emergent very close to Bansra Gali, Chitta Mor, Sunny Bank, and Kuldana. The road encircles the Murree town, starting from Bansra Gali to Kuldana and to Jhika Gali and then from Jhika Gali to Lawrence College and ending at the Bansra Gali intersection (figure 1b). Most part of the central ridge on which the Murree town is located is a SW plunging syncline with the Murree Formation lying in the core of syncline, with the beds dipping towards core of the ridge. This provides a degree of structural stability to the ridge.

These are potentially weak zone slopes and their strength is less than the surrounding intact rock (Malik and Farooq 1996). Presence of small shear zones in shale beds further reduces the strength and crucial for its stability. These deformation forces are determining factors for slope instability (Chambers 1992; Iqbal and Bennert 1998).

3. Material and methods

Seismic refraction method involves introduction of sound waves that refract from base of weathering and results in highlight bed rock distribution (Sass *et al.* 2008). For seismic refraction method, a 24-channel McSeis-1500 instrument of OYO Japan was used with a sledge hammer of 20 kg strike on an aluminum plate. The lines were oriented across the strike of the beds indicating the effect of weathering and compaction of the material in different rock types. The total number of strikes were 24, covered the spread length of 95 m and strikes

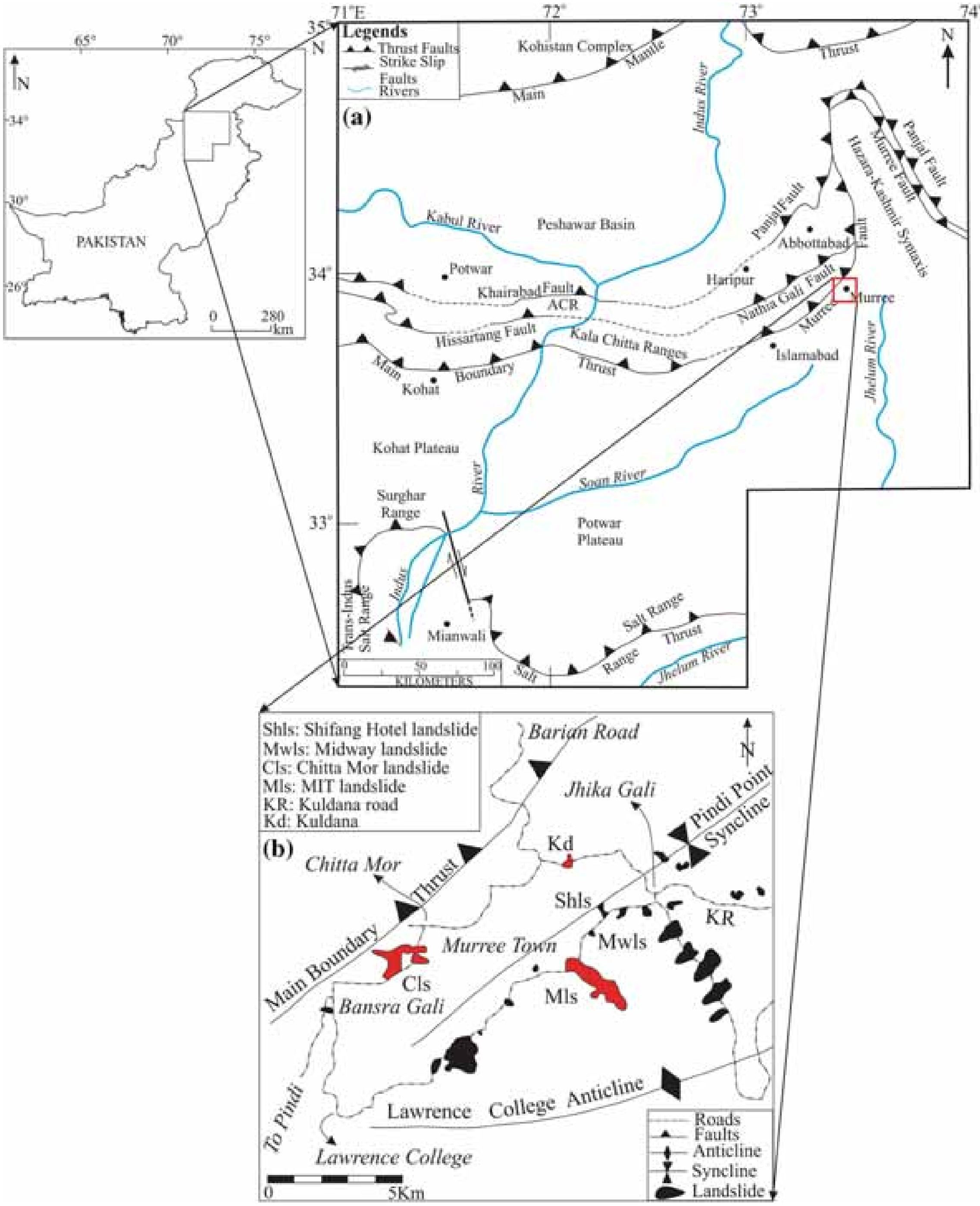

Figure 1. (**a**) Tectonic map of study area, showing major structural boundaries and study area with rectangle (red colour) (after Hylland *et al.* 1988). (**b**) Detailed location and landslide distribution map of Murree town and surrounding area. Most of important landslides along the Bansra Gali–Jhika Gali–Lawrence College ring road, and Jhika Gali–Bhurban sections are marked. Main Boundary Thrust (MBT) is oriented NE–SW direction. Studied landslides are highlighted as red colour (after Abbasi *et al.* 2002).

were spaced 2.5 m from strike points 1–5 and 20–24 while a spacing of 5 m was set from strike points 6 to 19. The refracted arrivals coming from base of different layers were received by geophones placed on the surface. The data was processed by using Pickwin 95 software. This software displays the refracted arrivals in terms of horizontal distance of geophones and arrival times of waves. Before picking these arrivals for extraction of time and distance data, a correction was carried out involving removal of traces that did not align themselves with respect to other traces (noises).

After picking the refracted arrivals a graph indicating the arrival times and distance is generated, data from all the points is plotted on that graph and a best fit line is passed covering maximum data points. The elevation correction is applied through Hagedoorn's plus minus method (Hagedoorn 1959) which uses a fixed reference point and moves source and receivers to that point, thus eliminating effect of elevation. The slope of the best fit line is analyzed for velocity of different subsurface layers which upon multiplication with time gives us the depth and thickness of different subsurface layers.

Vertical electrical soundings (VES) using Schlumberger configuration were carried out with an instrument ABEM SAS 1000/4000 Terrameter. This instrument records the consecutive readings and averages the results. The geoelectric data obtained were interpreted with partial curve matching and computer iteration using IPI2Win (2001) software.

VES survey was carried out with current electrode separation (AB/2), starting from 5 m to a maximum length of 100 m. The potential electrode separation (MN/2) was 1, 2, 5, 10, and 15 m. The increase of potential electrode separation MN allowed that readings from the same current electrode spread AB with the previous and expanded MN were taken. In this process, apparent resistivity was calculated using $R = (\Delta V * K)/I$, where $R =$ apparent resistivity; $\Delta V =$ potential difference; $I =$ current and $K =$ Schlumberger geometric factor. The data is further processed for the determination of true resistivity values by plotting the values of the apparent resistivity against the values of the half electrode spacing on a logarithmic scale in IPI2Win software. Field curves were generated after and the number of inflections on the curve was used for the estimation of layer resistivity and thicknesses. Various lithologies have been assigned on the basis of a standardized resistivity values. A default value of 2.5% is set by the IPI2Win software as the weighted root mean square (RMS) error.

In this study, for radon emanation, a passive detection technique was applied using Solid State Nuclear Track Detector (SSNTDs) CN-85. Passive radon detectors were fixed in tubes, which were planted at every 20 m, i.e., from −40 to 140 m on the survey line. The retrieved films were chemically etched using NaOH so that the tracks were clearly seen and counted under the optical microscope. This density results are multiplied with calibration factor, the higher density depicts more subsurface stress, higher porosity and permeability, which are the indicators of fracturing at that location. Further these results were also correlated with geological aspects to get a regional trend.

4. Results and discussion

4.1 *Geological sketches*

The three selected landslides are analyzed one by one and their results are interpreted and discussed separately. The general conditions of the surface features at the survey lines are shown in the sketches (figure 2). These sketches are representation of the type and nature of the material present at different positions along the survey profile. In addition, the position of streams, road and concrete retaining walls have also been marked. Loose material is present in the study area which is the source of vegetation in that region. Rocks are exposed along the road and have alternate beds of sandstone and shale dipping at low to steep angles. Most of the streams are at the contact of two lithologies indicating weak zone for water to make its way or otherwise in fractured sandstone that makes boulders to fall down, which deepen the streams further. All the three lines are oriented across the strike of the geological formations.

4.1.1 *Chitta Mor landslide*

Figure 2(a) depicts the sketch of Chitta Mor landslide. On the road from Rawalpindi to Murree, alternate layers of sandstone and shale are present between the positions from beyond −40 to −20, 0–10, 30–40, 100–115, and 130–140 m and above. Five streams cut their way through this small section (Asghar 2001). The locations of these streams and type of material in the stream beds are: (1) 12–15 m (sandstone), (2) 10–12 m (at the contact of sandstone and shale), (3) 72–73 m (shale), (4) 110–115 m (at the contact of sandstone and shale), and (5) 135–140 m (sandstone). Three of these streams are perennial whereas two are seasonal. The area above road (upslope) is covered with thick vegetation, whereas the area below road (downslope) is almost barren probably due to erosion. Many catchments have been built upslope. Also, one concrete retaining wall has been made on

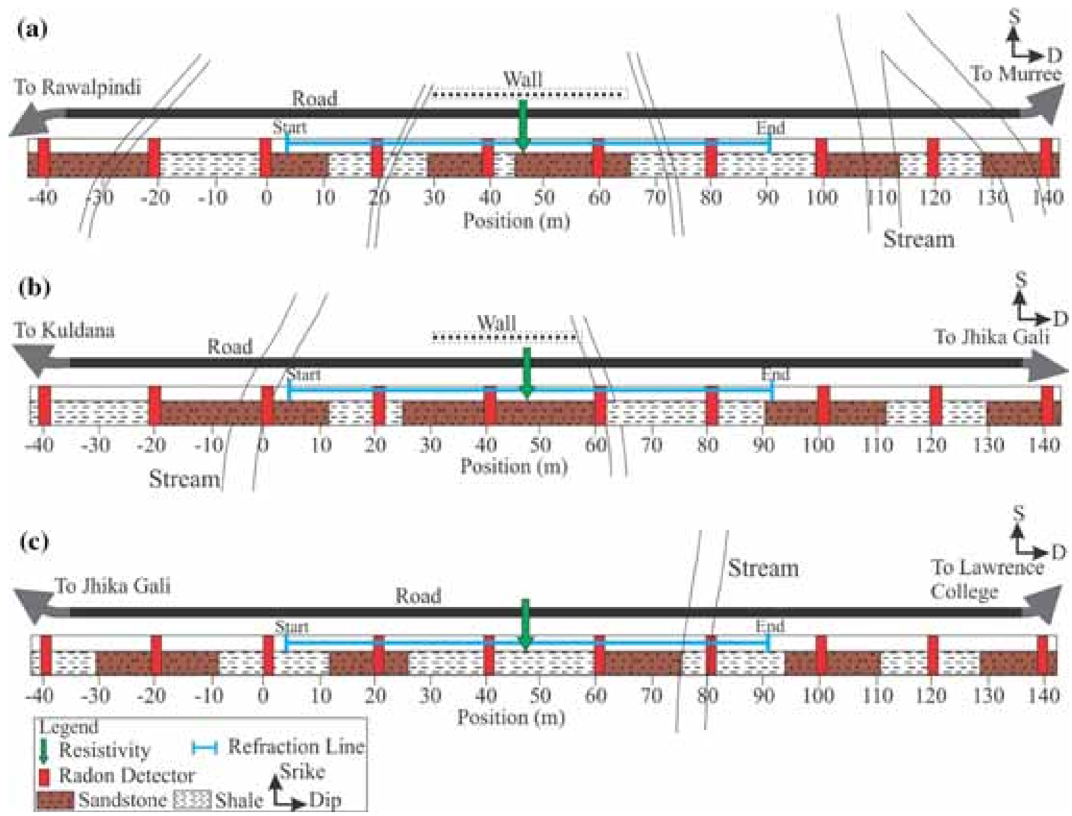

Figure 2. Sketch of landslides represents the position alternate layers of sandstone and shale from (**a**) Murree–Rawalpindi road (Chitta Mor), presence of one concrete retaining wall is shown on the downslope side of the road; (**b**) On road between Kuldana–Jhika Gali (Kuldana), one concrete retaining wall is present just below the road on the downslope side. The drains are damaged at some places due to mass movement; (**c**) Between Jhika Gali–Lawrence College road (MIT), a few catch water drains are present above the road, but no concrete wall has been made to support the material from sliding.

the downslope side of the road. The drains are damaged at some places due to movement of the material.

4.1.2 *Kuldana landslide*

Figure 2(b) shows the sketch of Kuldana landslide. Sandstone is present at four places from left to right, (i.e., from Kuldana to Jhika Gali side) between the following positions −20 to 10, 25–60, 90–110, and 130–140 m, with shale at intermediate places. Only two small streams are flowing downslope through this section. The first stream is perennial and passes through the sandstone between positions −5 and 0 m. The second stream, which is a lined catch water drain, is located between 60 and 62 m positions and flows along the contact of sandstone and shale. The area above the road is covered with thick vegetation whereas the area below the road (downslope) has moderate vegetation. One concrete retaining wall is present just below the road on the downslope side. The drains are damaged at some places due to mass movement.

4.1.3 *MIT landslide*

Sketch of the MIT landslide is shown in figure 2(c). Sandstone is present, from left to right, when facing downslide, between the positions from −30 to −10, 10–25, 55–75, 95–110, and 130–140 m and beyond. Only one stream is passing through the contact line of sandstone and shale between 75 and 80 m positions. The area above (upslope) and below (downslope) the road is devoid of any vegetation. A few catch water drains are present above the road, but no concrete wall has been made to support the material from sliding.

4.2 *Seismic refraction*

Figure 3 depicts the subsurface picture of Chitta Mor, Kuldana and MIT landslides obtained by seismic refraction method. The weathering layer

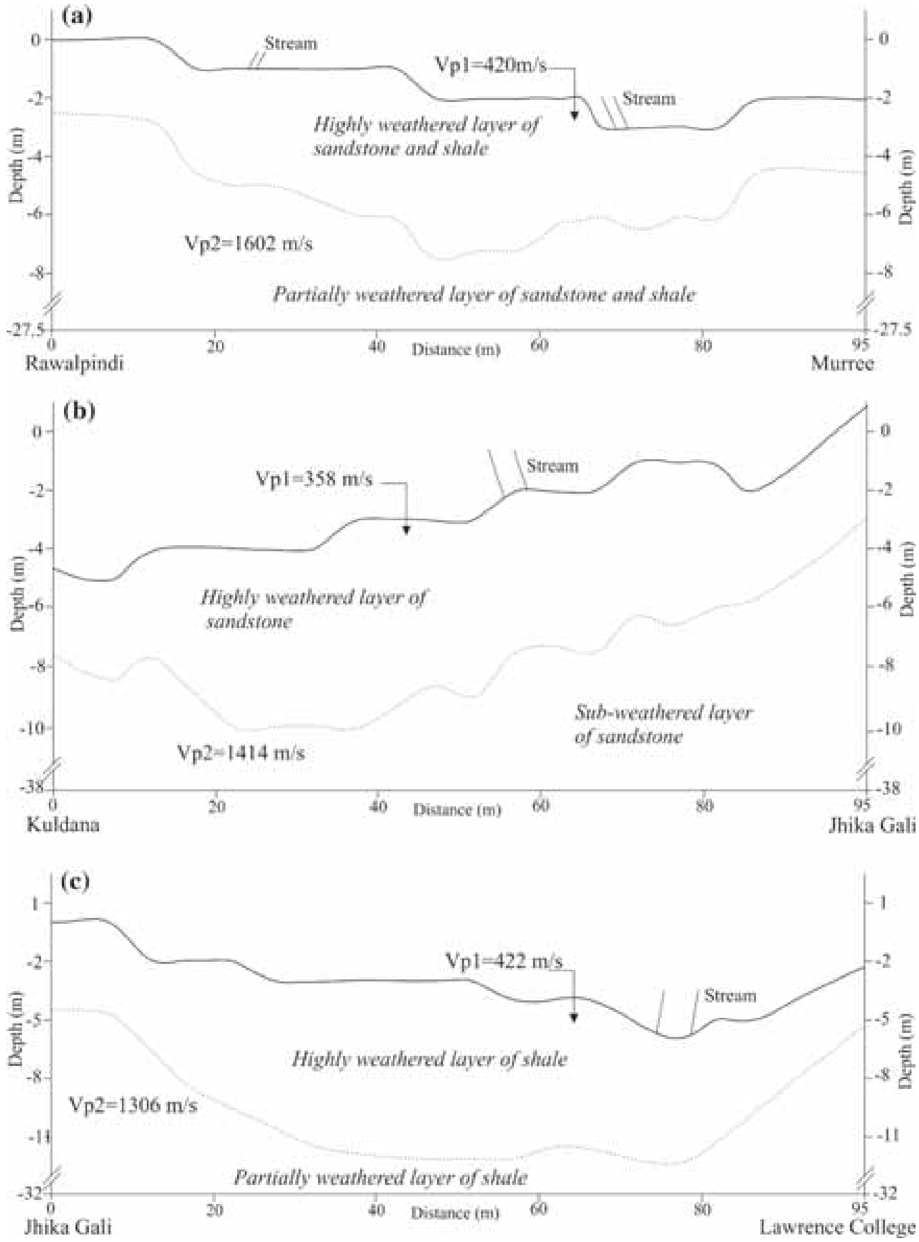

Figure 3. Seismic Refraction results at (**a**) Chitta Mor, (**b**) Kuldana, and (**c**) MIT landslides.

velocity was calculated as 420 m/s (Chitta Mor), 358 m/s (Kuldana) and 422 m/s (MIT), which shows that material is highly weathered. The thickness of weathered layer varies from 2.7–5.5 m (Chitta Mor), 6–10 m (Kuldana) and 4.5–9 m (MIT). The maximum thickness lies at position 50 m in the middle of the Chitta Mor profile, 20–30 m towards Kuldana side and 30–50 m at MIT. The second layer velocity is calculated as 1602 m/s (partially weathered), 1414 m/s (sub-weathered), 1306 m/s (partially weathered) at Chitta Mor, Kuldana and MIT landslide, respectively. The thickness of 2nd layer varies from 25–27.5, 36–38 and 25–32 m at Chitta Mor, Kuldana and MIT landslide, respectively. The second layer slopes towards east (Murree side) at Chitta Mor, towards Kuldana at Kuldana landslide and Jhika Gali in the northeast side at MIT.

4.3 *Electrical resistivity survey*

The resistivity probe position at all the sites is 47.5 m, i.e., exactly mid-point of the survey line and refraction profile. Figure 4 shows the resistivity values and thicknesses of different layers of subsurface material at Chitta Mor, Kuldana, and MIT landslides. The surveys were carried out after

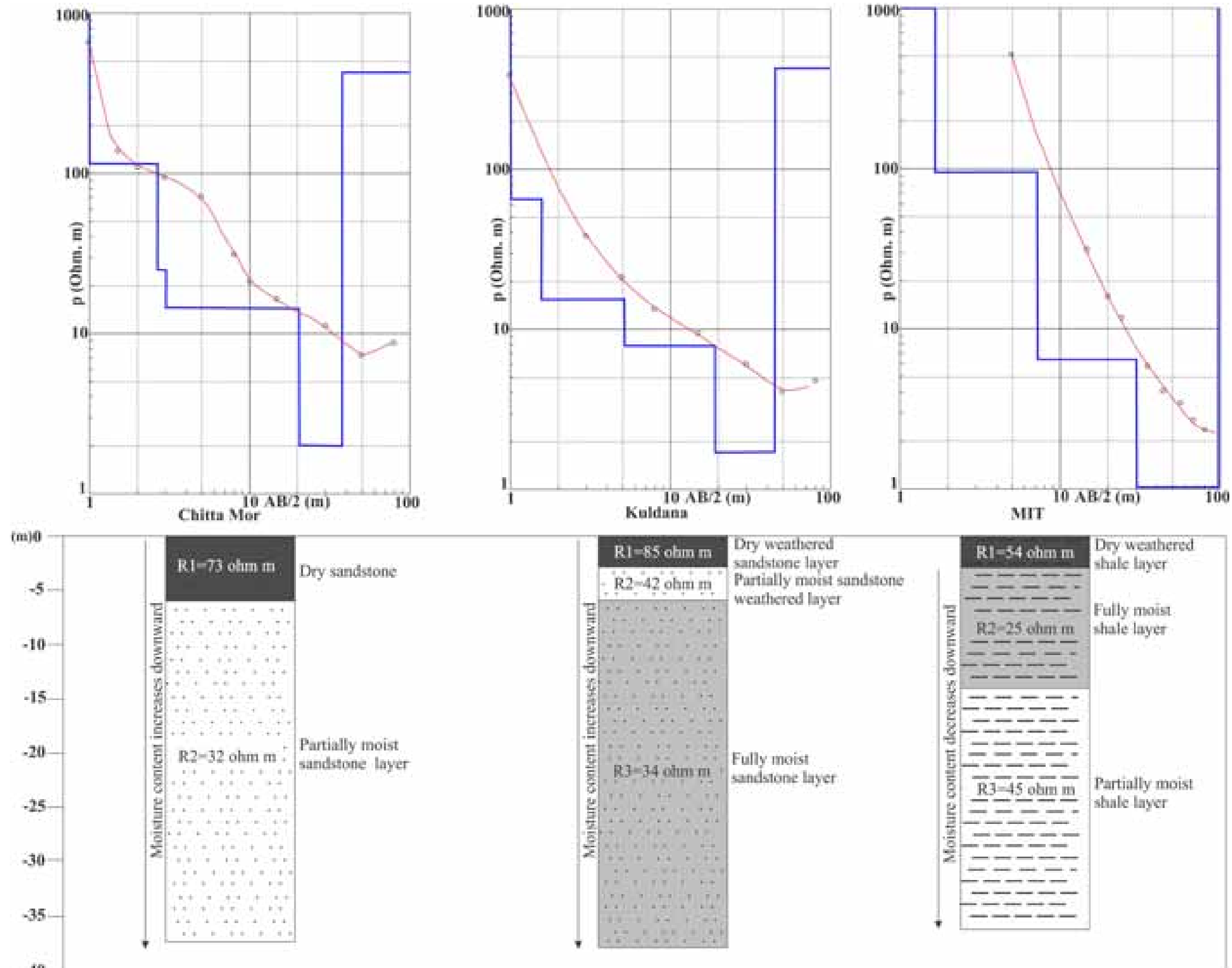

Figure 4. True resistivity values and thicknesses of interpreted different layers of subsurface material. The blue line resembles number of layers and thickness while red line shows matching of master curve with field curve.

a long drought period. Due to rainfall on the selected landslides, a phenomenon of sediment flow, transportation and compaction is observed in the top three layers of subsurface material. The top soils are almost dry and in the deeper parts less moisture is expected and therefore, the data was collected little above the thickness of last layer.

The resistivity results of Chitta Mor landslide show that the top layer is dry sandstone with a thickness of 5.5 m. The second layer is 31.5 m thick having a resistivity value less than that of the top layer, which indicates that the moisture content has increased with depth.

The Kuldana landslide probe was positioned on the sandstone all around. This site has three layers on the basis of variation in the resistivity values of the subsurface material. The upper two layers are thin, i.e., each of 3 m thickness, probably the whole material is weathered, indicated by seismic refraction results. The top layer shows a resistivity value of 85 Ωm, whereas second has only 42 Ωm. This difference in resistivity values is due to the difference in water content. The third layer has a resistivity value of 34 Ωm and extends downwards.

At MIT site shale is present at the resistivity probe position. Like Kuldana landslide, three layers are detected here. The top two layers differ in resistivity value, but material seems to be the same. The 3 m thick surface layer is dry shale and lower 11.5 m are moist. The resistivity increases from 25 to 45 Ωm in the third layer and indicates that the moisture is decreasing with depth.

4.4 *Radon exhalation*

At Chitta Mor only five detectors out of ten were recovered from positions of 20, 40, 60, 120, and 140 m. At Kuldana landslide detectors of positions

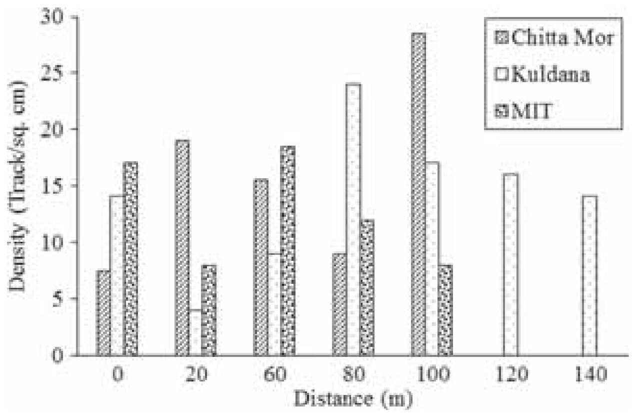

Figure 5. Track densities of radon exhalation at Chitta Mor, Kuldana and MIT landslides.

−40 and 80 m were lost (out of nine detectors planted) whereas no detector was planted at 140 m. The results of Kuldana radon exhalation are shown in figure 5. At MIT landslide, both the end positions were left empty and detectors from 80 and 120 m were not recovered. The track densities obtained from recovered detectors of this site are shown in figure 5.

The overall view of the observed track densities gives three evidences. Firstly, more gas is detected at the sites where sandstone is present as compared to the sites having shale. Secondly, the detector planted at the location having unstable subsurface material showed high radon densities as compared to stable material. Thirdly, high radon densities are observed with detectors close to streams and springs than the detectors located above dry material.

5. Causes of landslides in Murree Hills

1. The hill slopes in the Murree area are moderately steep. The slope angles vary from 40 to 50° in the upper side and 30–35° in the middle and lower sides. Thus, increase in steepness or slope gradient results in increase of shear stress at the potential failure plane and a decrease in normal stress (Malik and Farooq 1996).
2. Landslides are common consequence of earthquakes in hilly terrain. Earthquakes generated waves that travel through formation material of the rocks which results in fracturing. Ground shaking due to the vibrations in soil particles and rock masses, causes reduction in the friction which bonds them in place (Densmore and Hovius 2000).
3. The major cause of active mass movement process in Murree area is its incompetent lithologies and intense deformation, which cause the instability. Inter-bedded sandstone, siltstone and shale make over 70% of the area and are exposed on road cuts and natural excavations under a veneer of colluvium. With increase in moisture, these lithologies decompose rapidly to colluvium or residual soil and become vulnerable to land sliding.
4. In the study area, the surface and groundwater drainage system is not properly existed or generally inadequate. In precipitation, the water runoff is not only beyond control but also blocked by unplanned construction. The water infiltrate into the hill slope material and saturate the colluvium and results in triggering the slides.
5. The rise in tourist's influx has consequently increase the rate of construction of residential hotels, shopping centers, recreation centers, and concrete houses without proper consideration of slope stability. It has seriously disturbed the natural drainage system of fragile slopes and is under serious threat of soil erosion, disrupting the road network and landslides. Also, a large-scale project for construction of new roads and widening of old roads is under progress all around the Murree area, but unfortunately without any proper consideration of slope stability. Excavation at the toe of slope for building of these roads destabilizes the existing state of stress and promotes landslides.

6. Correlation of geophysical results with geology

A correlation of the results obtained by seismic refraction, electrical resistivity and radon exhalation with the geology shows that they are commonly supportive to each other. Comparing the results of refraction and resistivity method, it is evident that two weathered layers are detected by refraction method and one layer by resistivity method. It is possible that the velocity is same throughout the weathering layer, whereas the resistivity values vary due to difference in moisture content. The deeper parts of all the landslides are stable which is shown by high values of seismic velocity. It is to be noted that the seismic layers do not correspond to the single rock unit.

In addition, other factors like amount of precipitation in the form of heavy rain bursts in the monsoon season and snow in winter play a major role to destabilize the geological formations composed primarily of clay, silt and sand. Structurally the folds are asymmetric and competent Murree sandstone overlies the shale beds. The rapid erosion of shale due to heavy rains in July and August causes the overlying sandstone beds to collapse. Although, surface runoff is high due to steep slopes, even then some water percolates into the shale and sandstone beds and makes these lithologies wet. The low resistivity values on sandstones (Kuldana and Chitta Mor landslides) at a depth of 6 m and shale (MIT landslide) between 4 and 15 m is indicative of this fact that percentage of water content is high. Similarly, low values of seismic P-wave velocity indicate the weathering effect on these lithologies, water being one agent of weathering. The wetness makes the weathering layer unstable and as the load exceeds the stress limit, landslide is triggered.

From the results of radon densities, it is found that more gas is exhausted from thick and unstable weathering layer detected through refraction method (e.g., MIT position 40 m, although shale is present there) and less from thin weathering layer at stable places (e.g., MIT position 100 m, although sandstone is present there) respectively.

7. Conclusions

- All geophysical investigations indicate that mass movement in Murree Hills is due to the effect of heavy monsoon. The excessive rain increases the moisture content that ultimately increases the deformational forces and decreases the shear strength of the shale and sandstone.
- Presence of alternate bedding of sandstone and shale of Murree Formation, the shale lithology weathers easily and is eroded away leaving sandstone boulders uncovered, which slide down. Fractures and joints in the sandstone are also found responsible for producing boulders, which slip downslope.
- The road encircling the Murree ridge is generally unstable, particularly Jhika Gali to Lawrence College road section. The main reason is the relatively steeper slope, thin vegetation cover, sewerage disposal and large-scale new construction work in the area downslope the road.
- Increase in thickness of weathering layer in the central part provides space for accumulation of loose material, which exerts more downslide force and causes landslide. If these investigations are extended up to the limits of potential slope failure, a three-dimensional view of the whole landslide and surroundings can be found. Then, on the basis of type of the material and water content involved in any landslide, the forces acting per unit area at any specified location can be calculated. These calculations can lead to the decisions for remedial measurements.

Acknowledgements

The authors thank the National Centre for Physics (NCP) and Dr Shahid Nadeem Qureshi (Comsats University Islamabad) for the logistic support for field work and instrumentation used in this study.

References

Abbasi I A, Khan M A, Ishfaq M and Mool P K 2002 Slope failure and landslide mechanism, Murree area, north Pakistan; *Geol. Bull. Univ. Peshawar* **35** 125–137.

Asghar M 2001 Geophysical investigation of landslides in Murree Hills area; M.Phil thesis, Department of Earth Sciences, Quaid-i-Azam University, Islamabad, Pakistan.

Bharti A K, Pal S K, Priyam P, Kumar S, Srivastava S and Yadav P K 2016a Subsurface cavity detection over Patherdih colliery, Jharia Coalfield, India using electrical resistivity tomography; *Environ. Earth Sci.* **75**(**5**) 1–17, https://doi.org/10.1007/s12665-015-5025-z.

Bharti A K, Pal S K, Priyam P, Pathak V K, Kumar R and Ranjan S K 2016b Detection of illegal mine voids using electrical resistivity tomography: The case-study of Raniganj coalfield (India); *Eng. Geol.* **213** 120–132.

Bharti A K, Pal S K, Saurabh, Singh K K K, Singh P K, Amar Prakash and Tiwary R K 2019 Groundwater prospecting by inversion of cumulative data of Wenner–Schlumberger and Dipole–Dipole arrays: A case study at Turamdih, Jharkhand, India; *J. Earth Syst. Sci.* **128(4)** 107, https://doi.org/10.1007/s12040-019-1137-2.

Bichler A, Bobrowsky P, Best M, Douma M, Hunter J, Calvert T and Burns R 2004 Three-dimensional mapping of a landslide using a multi-geophysical approach: The Quesnel Forks landslide; *Landslides* **1(1)** 29–40.

Chambers A F 1992 Kinematics of the frontal Himalayan thrust belt, Pakistan and the external Western Alps, France; unpublished Ph.D dissertation, Imperial College London, 369p.

Chirkov A M 1975 Radon as a possible criterion for predicting eruptions as observed at Karymsky volcano; *Bull. Volcanologique* **39**(**1**) 126–131, https://doi.org/10.1007/BF02596952.

Densmore A L and Hovius N 2000 Topographic fingerprints of bedrock landslides; *Geology* **28(4)** 371–374.

Deoja B M, Dhital B T and Wagner A 1991 Mountain Risk Engineering Handbook-Part 1, International Center for Integrated Mountain Development, Kathmandu, Nepal.

Dunning S A, Mitchell W A, Rosser N J and Petley D N 2007 The Hattian Bala rock avalanche and associated landslides triggered by the Kashmir Earthquake of 8 October 2005; *Eng. Geol.* **93(3)** 130–144.

Dyck W 1972 Radon methods for prospecting in Canada, Uranium prospecting Handbook. In: *Proceedings of NATO Sponsored Advanced Studies Institute, on methods of Prospecting of Uranium Minerals*, London.

Farooq S M 2000 Geotechnical study for landslide problems along Murre Muzaffarabad Road Pakistan; PhD Thesis, University of Punjab, Lahore, Pakistan.

Gansser A 1964 *Geology of the Himalayas*; Wiley, New York, 289p.

Gupta R K, Agrawal M, Pal S K, Kumar R and Srivastava S 2019 Site characterization through combined analysis of seismic and electrical resistivity data at a site of Dhanbad, Jharkhand, India; *Environ. Earth Sci.* **78(6)** 226, https://doi.org/10.1007/s12665-019-8231-2.

Hafeez S, Ahmed W, Azam S and Khan S 2019 Evaluation of landslide hazard at Herth, Chitral, Pakistan; *Innov. Infrastruct. Solut.* **4** 13.

Hagedoorn J G 1959 The plus–minus method of interpreting seismic refraction sections; *Geophys. Prospect.* **7** 158–182.

Hylland M D, Riaz M and Ahmad S 1988 Stratigraphy and structure of southern Ghandghar Ranges, Pakistan; *Geol. Bull. Univ. Peshawar* **21** 1–14.

Ibsen M L and Casagli N 2004 Rainfall patterns and related landslide incidence in the Porretta–Vergato region, Italy; *Landslides* **2(1)** 143–150.

IPI2Win 2001 Programs set for ID VES data Interpretation; Department of Geophysics, Geological Faculty, Moscow University, Russia.

Iqbal M and Bennert D 1998 Structural observations of the Margalla Hills, Pakistan, and the nature of the MBT; *Pak. J. Hydrocarbon Res.* **10** 41–53.

King C Y 1978 Radon emanation on San Andreas fault; *Nature* **271** 516–519.

Malik M H and Farooq S 1996 Landslide hazard management and control in Pakistan: A review of ICIMOD; Kathmandu, Nepal, 68p.

Montogomery C W 1991 *Environmental Geology*; 3rd edn, Wm C. Brown Publishers, Dubluque, IA52001, USA.

Neiderer S and Schaffner U R 1989 Landslide problems and erosion control in Murree and Kohat tehsils of Rawalpindi Dist.; Results of the fact-finding mission, Swiss Dev. Coop, Ministry of Foreign Affairs, Govt. of Switzerland, CH-3003, Bern, 38p.

Rafiq M, Khan S R, Wagner A and Stephan N 1989 Murree Erosion Control; Results of the fact-finding mission, Swiss Dev. Coop, Ministry of Foreign Affairs, Govt. of Switzerland, CH-3003, Bern, 38p.

Ranjan S K, Pal S K and Singh K K K 2015 An approach to improve shallow surface investigation using Joint analysis of Rayleigh and Love waves; *Curr. Sci.* **109(7)** 1239–1242.

Sass O, Bell R and Glade T 2008 Comparison of GPR, 2D-resistivity and traditional techniques for the subsurface exploration of the Öschingen landslide, Swabian Alb (Germany); *Geomorphology* **93(1)** 89–103.

Schaffner U R 1998 Landslide management and construction of roads in hilly areas of Murree and Kahuta; Report by Govt. of Punjab, 22p.

Singh K K K, Bharti A K, Pal S K, Prakash A, Saurabh, Kumar R and Singh P K 2019 Delineation of fracture zone for groundwater using combined inversion technique; *Environ. Earth Sci.* **78** 110, https://doi.org/10.1007/s12665-019-8072-z.

Ulomov V I and Mavashev B Z 1967 On force runners of strong tectonic earthquakes; *Dokl. Akad. Nauk. USSR* **176** 319.

Young D A 1956 Etching of radiation damage in lithium fluoride; *Nature* **182** 375–377.

Corresponding editor: Arkoprovo Biswas