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Rain-Induced Slope Instability: Case Study of Monsoon 2020 Affected Villages in Pithoragarh District of Uttarakhand, India

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INFORMATION

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ABSTRACT

Heavy precipitation in the catchments of Ramganga, Goriganga, Dhauliganga and Kali Rivers between 19 and 29 July, 2020 induced landslides and debris flows around many villages of Pithoragarh District of Uttarakhand in India. Additionally, heavy rains added to the discharge of streams and the ensuing floods damaged some of the villages among those were located in the proximity of the streams.15 villages of Tejam, Munsiyari, Bangapani and Dharchula Tehsils of Pithoragarh District were badly affected in these incidences. Except for, there was massive loss of public infrastructure and property together with electricity and drinking water supplies were disrupted as also vehicular traffic was disrupted due to road damaged or washed off in the affected areas. Total of 28 human lives lost in entire Pithoragarh District during the monsoon period. In terms of losses of human lives, one of the worst affected villages was Tanga where alone 11 persons were killed and another was Gaila Malla Tok of Pattharkot Village where 3 persons were killed which caught Author attention to take these studies. The main purpose of this research is to find out the causative factors of slope instability and suggested measures for safety of dwelling units as well as local inhabitants in the villages.

1. Introduction

Easternmost frontier Pithoragarh District of Uttarakhand State is most vulnerable to a number of natural disasters like landslide, avalanche, flood, flash flood etc. Mostly habitations of the region are situated in Lesser and Higher Himalayan Terrain which separated by a major tectonic discontinuity as Main Central Thrust (MCT) passing across the Dhauliganga Valley near Munsiyari and Kali Valley near Tawaghat. It lies in the high Seismic Zone V of the Earthquake Zonation Map of Uttarakhand (IS: 1893 Part I, 2002) and earthquakes of 1979 and 1980 in Dharchula Tehsil ravaged several villages along the Kali Valley. In recent decades, the area is observed to be affected by cloudburst/ heavy localized precipitation events resulting in heavy losses of lives, properties and infrastructures along with natural resources (Khanduri, 2020).

In the year 1998, a massive rock fall took place at Malpa Village in Dharchula Tehsil of Pithoragarh District due to excessive rainfall caused more than 200 persons were killed in this incidence (Paul et. al., 2000). Because of huge landslide mass placed over Malpa Gad resulted blocking its course temporary (Khanduri, 2021). Likewise, in the year 2005, near Dharchula and Munsiyari areas were badly affected due to cloudburst and heavy rainfall in which washing away of a number of agricultural fields along with a bridge at Syangatha. On the other hand, Madkot area of Munsiyari has been destroyed due to lake formation by the Goriganga and Kali Rivers (Das et. al., 2006).

Similarly, in the year 2009, landslide disaster occurred on Kuity Village on Berinag - Munsiyari Road caused the Jhakhala and Lah Villages were washed away wherein losses of 43 human lives (Kumar, 2013). In August, 2010 cloudbursts occurred on Munsiyari area killing around 38 persons (Das, 2015).

June 2013 disaster occurred in catchment areas of major rivers like Ramganga, Goriganga, Dhauliganga and Kali Rivers due to torrential rainfall and caused several landslides.

This havoc led to the flash flood with huge sediment load causing unusual swelling of the rivers. The most affected villages in Pithoragarh District were around Munsiyari and Dharchula Tehsils (Bishwapriya et. al., 2013).

Similarly, during the monsoon of 2016 as well Didihat, Bastari and Naulra Villages of Pithoragarh District were devastated by debris flow and landslide incidences that took toll of 22 human lives (Khanduri, 2017). Likewise, localised heavy rains in the early hours of 14 August, 2017 in the catchment of the tributaries of Kali River, particularly Simkhola Gad and Malpa Gad, caused slope instability and damages in Mangti and Malpa areas respectively. As many as 9 persons were died while 18 persons went missing and 51 animals were lost in these incidences that caused heavy loss of other infrastructure and facilities (Khanduri, 2018). These disastrous events are clearly showing that the areas devastated by the slope instability and mass movement at present have been inherently vulnerable and have been repeatedly affected by various disasters in the past.

In monsoon 2020, excessive heavy rainfall insuring landslides and floods caused damages in 15 villages of the Munsiyari, Bangapani, Dharchula and Tejam tehsils of Pithoragarh district. These inflected massive losses of human lives, properties and infrastructures. According to District Disaster Management Authority, Pithoragarh District, total of 382 families as well as 19,185 population have been affected in these villages during monsoon 2020. The preliminary geological-geotechnical assessments of affected villages in Tejam, Munsiyari, Bangapani and Dharchula Tehsils of Pithoragarh District were carried out with the following objectives:

i) To assess the possible causes of slope instability in the villages among those affected by landslides and floods in Monsoon 2020,
ii) To categorize the affected villages in two portions, one wherein mitigation measure can be taken up and another most vulnerable villages,
iii) Providing site specific mitigation measures in affected villages for safety of property as well as local inhabitants,
iv) Suggesting rehabilitation for highly vulnerable villages among those have not been found suitable for habitations,
v) To safety of human being is a prime objective of this study.

Table 1. Tehsil wise details of affected villages along with coordinates

No	Tehsil	Affected village	Location/co-ordinate
1	Munsiyari	Dhapa	N 30°7'4" E 80°14'34.9"
2		Suring (Balota)	N 30°5'7.53" E 80°14'32.60"
3		Malupati	N 30°3'44.24" E 80°15'57.71"
4		Serasuidhar (Chana)	N 30° 5'24.05" E 80°15'33.48"
5		Josha (Ropad Tok, Sirwakhan Tok and Lorkhet Tok)	N 30°02'33.4" E 80°17'27.7"
6	Dharchula	Dharchula Dehat (Gwalgoan)	N29°51'6.1632" E 80°32'30.6168"
7		Galati (Dhami Tok)	N 29°51'19.30" E 80°29'29.91"
8		Khela (Chetkala, Kolpani and Ala)	N 29°57'57.51" E 80°35'28.80"
9	Bangapani	Bangapani (Talla Mori Tok)	N 29°54'22.02" E 80°18'43.37"
10		Bangapani (Choribagar Tok)	N 29°56'35.64" E 80°18'6.85"
11		Tanga	N 30°1'4.92" E 80°19'48.77"
12		Pattharkot (Gaila Malla Tok)	N 30°4'29.13" E 80°19'30.882"
13	Tejam	Ghatghorigari (Gat Tok)	N 29°55'5.86" E 80°9'29.124"
14		Khetbharar	N 29°55'35.87" E 80°13'56.13"
15		Khetali	N 29°55'35.10" E 80°14'14.22"

2. Materials and Methods

2.1. Location of affected villages

The area under present investigations lies in the Higher and Lesser Himalayan regions of Pithoragah District of Uttarakhand in India. The present study focuses upon slope instability in the villages wherein intense rainfall ensuring floods and landslides damages were occurred. Details of affected villages along with coordinates are given in the Table 1 and the location of same villages is shown in Fig. 1.

2.2. Methodology

This study is largely based upon observations made during the fieldwork undertaken in Pithoragarh District on the aftermath of Monsoon 2020. The field investigations were undertaken between 27 August and 7 September, 2020. Site inspection and other investigations were carried out in the presence of the concerned Patwari, Gram Pradhan and local inhabitants. Based upon the investigations carried out in the area site specific mitigation measures/suggested measures have been incorporated in this paper.

2.3. Physiography and rainfall

The area represents high mountains and valleys exhibit very rugged topography wherein the ground elevations generally vary between 950 and 4,000 m asl. These are characterized by moderate to steep slopes that are intervened by narrow valleys. Mostly, high mountains and peaks of the area remain snow covered. Some of the well-known mountains and peaks of the area include Sunanda Devi (7,434), Trishuli (7,099), Panchchuli II (6,904), Chhota Kailash (6,310), Nanda Pal (6,306), Bamba Dhura (6,334), Om Parvat (6,191).

Geomorphic features of fluvial/fluvio-glacial and colluvial origins are generally observed in the area. High relative relief along with presence of thick overburden and heavy precipitation make this region prone to landslides. The prominent major streams of the area are Ramganga, Goriganga, Dhauliganga and Kali Rivers. The Kali River flows Southwesterly direction and all the aforesaid rivers are the major tributaries of the same. It also forms the international boundary between India and Nepal. The rivers and their tributaries in the region are generally flow with great force through steep and narrow channels; often resulting in excessive bank erosion.

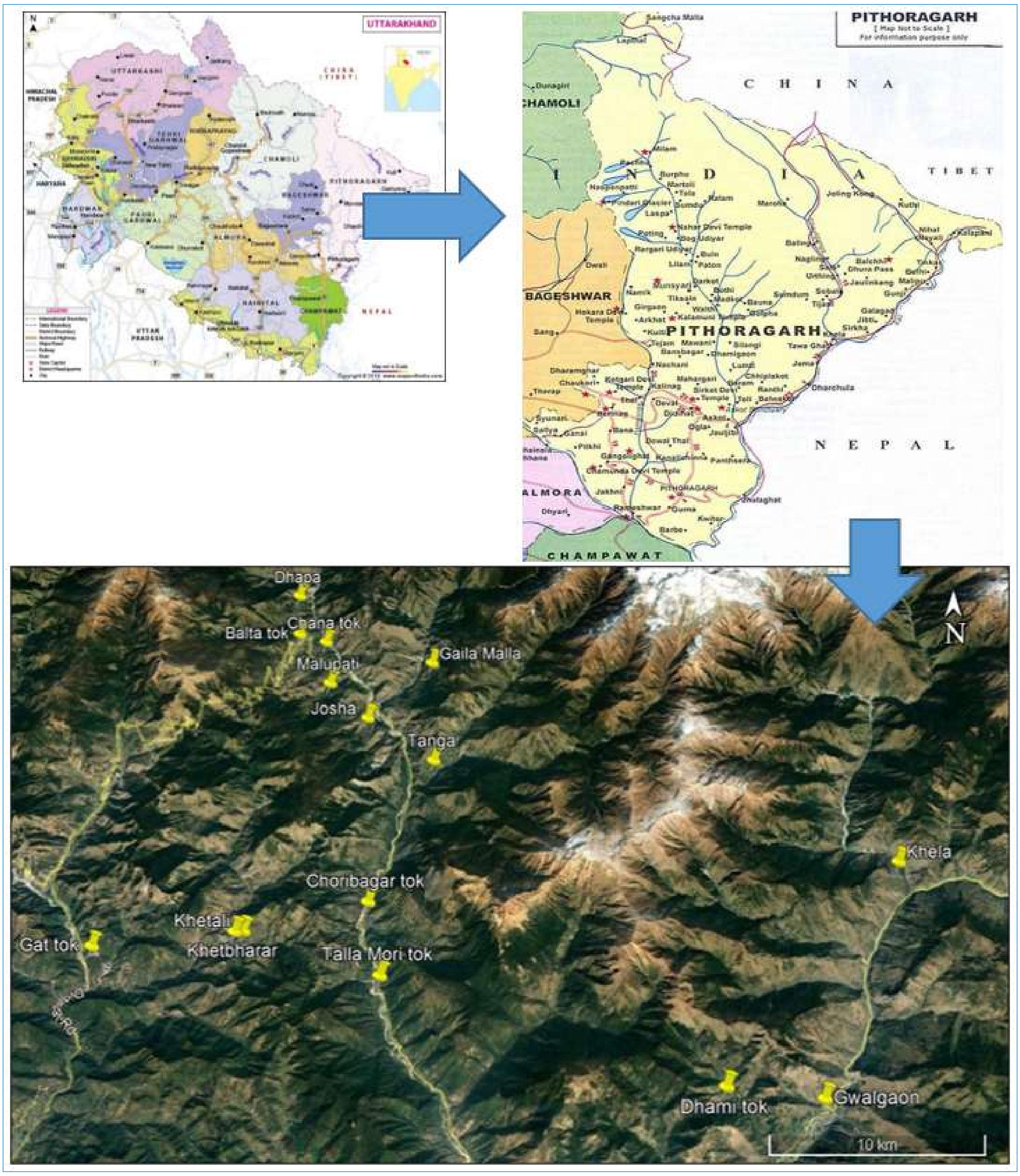

Fig. 1. Location map (Courtesy: Internet and Google Earth Pro)

The entire Pithoragarh District experiences rainfall in sufficient amount because of Southwest Monsoon during June to September months. The precipitation mainly arises during the summer while scattered rain arises during winter months. The average monthly rainfall data of Munsiyari and Dharchula Tehsils of Pithoragarh District is given in Fig. 2. The rainfall data indicate that the Munsiyari and Dharchula Tehsils have been recorded an average maximum rainfall 889 mm and 1281.6 mm in the month of July 2020, respectively.

The affected villages under the present study mostly falls between Didihat and Dharchula Tehsils. Consequently, the rainfall data in the month of July in Munsiyari and Dharchula Tehsils of Pithoragarh District was collected and summarized in Fig. 3.

The rainfall data of different region reflect that variable rainfall distribution because of geomorphic and orographic disposition. This rainfall data reflects that excessive rainfall was recorded in Munsiyari Tehsil on dated 19-20 July, 2020 while in Dharchula Tehsil on dated 20 July, 2020. Furthermore, excessive rainfall was recorded in Dharchula Tehsil on dated 28-29 July, 2020 which was observed much higher than previous. This triggered landslide and debris flow at many villages of Tejam, Munsiyari, Bangapani and Dharchula Tehsils. Gaila Malla Tok of Pattharkot and Tanga Villages in Bangapani Tehsil of Pithoragarh District were worst affected in terms of losses of human lives.

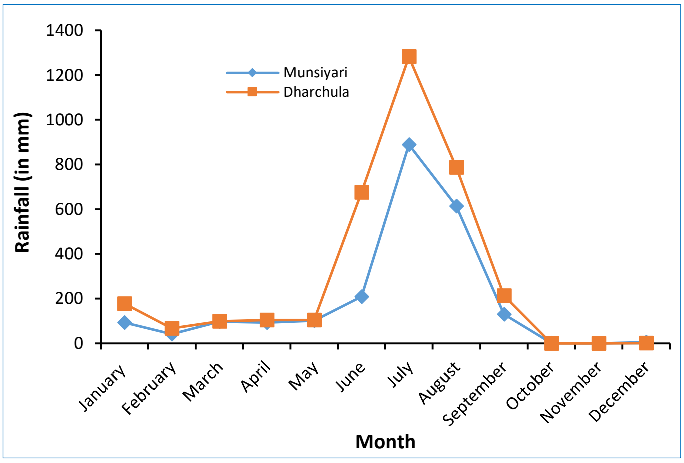

Fig. 2. Average monthly rainfall in Munsiyari and Dharchula Tehsils of Pithoragarh District for year 2020

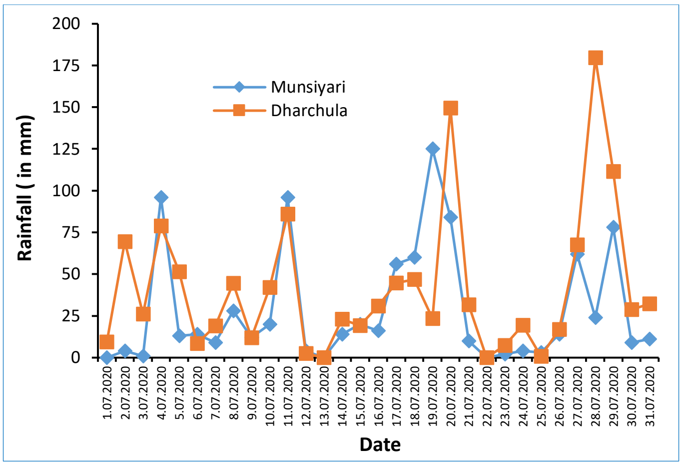

Fig. 3. Rainfall in the month of July in Munsiyari and Dharchula Tehsils of Pithoragarh District

2.4. Geological setting

Geologically, the area of investigations in Pithoragarh District lies in Higher Himalayan and Lesser Himalayan terrain. The MCT is a Northeasterly dipping major tectonic plane which separates Central Crystalline Groups of rocks of Higher Himalaya from Lesser Himalayan meta-sedimentary rocks which is passing North of Tawaghat in the Kaliganga Valley whereas North of Munsiyari in the Goriganga Valley in this region. The area under the present study exposes rocks of Central Crystallines, Garhwal Group and Chiplakot Crystalline of Almora Group intruding into the Garhwal Group of rocks (Auden, 1949; Heim and Gansser, 1939; Valdiya, 1980; Patel et al., 2007).

The rocks of Central Crystalline Group are represented by Munsiyari Formation. It comprises biotite gneiss, augen gneiss, mica-garnetiferous schist, migmatites. The rocks of Garhwal Group are represented by Rautgara, Pithoragarh and Berinag Formations. The Pithoragarh Formation is divisible into lower and upper members. The Lower member comprises stromatolite bearing dolomitic limestone, calcareous phyllite, quartzite and marble. The Upper member consists of dark grey calcareous slate and limestone. Berinag Formation comprises quartzites interbedded with meta-volcanics, gneisses and slates. Rautgara Formation comprises quartzites interbedded with meta-volcanics and slates. The Chiplakot Crystallines exposed in the study area are granitoid intrusives in the Garhwal Group that comprises biotite granite gneiss.

3. Causative Factors of Slope Instability in Villages

The Pithoragarh District experiences heavy downpour resulting in added the discharge of streams/rivers ensuing floods damaged various villages that were located in the proximity to streams. Additionally, underground seepage saturated the weathered rock slopes as well as overburden slopes resulting in landslides and subsidence in the villages. Apart from, anthropogenic activities like road widening, new road construction and unplanned debris disposal aggravated the problems in some of the villages. Some of the major causative factors of slope instability are given below:

- ✓ Heavy downpour or heavy localized precipitation in the area,
- ✓ Construction in the proximity to thrust/fault zone without taking earthquake safety norms,
- ✓ Presence of loose soils and unconsolidated materials around the area,
- ✓ Saturation of loose materials and weathered rock slopes by underground seepage,
- ✓ Construction of houses in the proximity to the streams/rivers,
- ✓ Construction of houses over the natural depression and water ways,
- ✓ Encroachment in the course of streams,
- ✓ Over excavation of hillside slope for widening of road without taking care of proper slope protection,
- ✓ Dumping of excavated materials along the valley side of road area,
- ✓ Lack of proper debris disposal,
- ✓ Road side drains not properly constructed,
- ✓ Insufficient discharge carrying capacity culverts,
- ✓ New road construction upslope of the village area having with steep slope,
- ✓ Overloading of overburden slopes by heavy constructions,
- ✓ Construction in bottom of high hills and low laying areas,
- ✓ Construction in limestone terrain without making proper adequate drainage arrangement,
- ✓ Ill management of household waste water disposal and
- ✓ Construction of houses on the steep slope without making suitable platform.

Among these are largely responsible for damages and destructions during the monsoon 2020 in the aforesaid villages.

4. Observations Along with Recommendations in Affected Villages

As a list of 15 villages had been provided by the District Authority, accordingly field investigations were carried out in the same villages on the aftermath of post monsoon. Observations were made in these villages are given in sections separately below:

4.1. Dhapa (N 30°7'4" E 80°14'34.9")

Heavy localized precipitation/cloudburst like incidence took place around Dhapa area on 19 July, 2020 in early morning whereas it had been raining heavily from 18-20 July, 2020 continuously. The upslope of road area was observed to have sub-vertical rocky cliff at top whereas middle portion of the hill slope thick overburden cover are observed having with moderately steep to very steep slope (45°-60°). Mostly, the habitation is situated along the course of these streams just below the road head and on gentle sloping terraces. The uphill slope in the affected area is generally observed dip towards East at steep angles with N-S trending ridge. The area is surrounded by dense forest cover.

Exposures of Central Crystalline gneisses are observed along the road section around the village. These are generally observed to strike E-W with moderate dips towards due N. Other two prominent joints were observed to dip towards SSW and ENE at steep angles (60°/200° and 55°/80°). The three small streams namely De Dhar nala, Chhida Nala and Humti Nala are flowing through the same slopes. The east flowing streams together with water saturated boundary debris are observed to have overrun residential houses of the village (Fig. 4a). Steep slope accompanied with heavy discharge of water saturated debris with boulders is deduced to have aggravated the pace of erosion along the streams and had high erosion potential to create deep gullies through the village (Fig. 4b).

Fig. 4. Heavy rains triggered debris flows related damages and destructions in Dhapa Village; (a) houses destroyed by water saturated bouldary debris, (b) deep gully due to fast pace of erosion by stream, (c) bouldary debris accumulated in agricultural fields and (d) landslide triggered by water action

Amongst these, 4 houses were destroyed while the others 13 houses were partially damaged and filled with debris. Total of 8 Cows and 8 Goats were lost while a child with his mother flowed down with water saturated debris and seriously injured in these incidences. The bouldary debris flows that descended down from the area upslope of the village was also observed to have overrun road and a number of agricultural fields (Fig.4c).

Apart from a major debris slide is to be observed on the valley side slope having steep gradient due to aggressive gully erosion by the streams and excessive rains (Fig.4d).

Recommendation: Geologically, the Dhapa Village is not found suitable for habitation because of habitation placed on stream course and activation of overburden materials which laid on uphill slope have the potential of posing danger to the village, particularly during heavy or prolonged rainfall which may flow down with the streams. It is therefore advised that the inhabitants of the affected area should be evacuated to safer places before the onset of monsoon.

4.2. Balta Tok (N 30°5'7.53" E 80°14'32.60")

Heavy discharge of water saturated debris flows through the stream and adjacent slope after the heavy rains descended down from the upslope of the Balta Tok of Suring Village having with steep slope which were overran habitations and agricultural fields. Exposures of Central Crystalline banded gneisses are observed along the road section around the tok. Rocks exposed in the area are generally observed to strike NE-SW with moderate dips towards NW. Other two prominent joints were observed to dip towards SSW and NNE at steep angles (65º/200º and 65°/35°). Indiscriminate hill side cutting for road widening and unplanned debris disposal along the road aggravated the problem during spells of heavy downpour (Fig. 5a). This debris that descended down from the area upslope of the tok was observed to have overrun both agricultural fields and partially damaged some houses (Fig. 5b). This debris materials are observed to comprise of hill wash and debris consisting of gray to grayish brown, fine grained silty matrix with rare boulders and fragments of gneisses and metabasics. There was a partially constructed toe drain along the hill side Munsiyari-Madkot Road which was found insufficient to carry the monsoon discharge (Fig. 5c).

Fig. 5. Heavy rains triggered debris flows and related damages in Balta Tok; (a) undercutting of hill slope for road widening; (b) debris flows from uphill road overrun agricultural fields and houses; (c) severally damaged culvert due to excessive water saturated debris discharge by local stream; (d) unlined and chocked hill side drain on road due to debris flows

A small perennial stream having gentle to moderate slopes was observed to flows through the area. Water saturated debris flows through this stream which had severally damaged the culvert and overflows through the road due to heavy precipitation (Fig. 5d). It was observed that the size and gradient of the culvert was not enough to passes the desired discharge. In the proximity to this stream a gully has been developed as because of water saturated debris flows which has ultimately posing a stability danger to a house which is located just below the road head.

Recommendations: The hill slope cutting for widening of the road around the Suring bend area posed threats of slope failure to the downhill side habitations. Therefore, suitably designed retaining walls of appropriate height would have to be constructed on hill side of the road. Landslide debris is required to be removed from the agricultural fields so that these are put to productive use by the villagers. In order to control the flow of water of the stream in the area, the channel bed is required to be turned into a series of cascades and construction of a new culvert of maximum discharge carrying capacity. This would help in protecting the tok from excessive rise in pore water pressure during the monsoon. Construction of lined drain with suitable gradient along the hillside road and connecting it into the nearest natural depression/stream.

4.3. Josha (N 30°02'33.4" E 80°17'27.7")

Heavy downpour occurred in the area around Josha Village on 18 July, 2020 caused heavy damage to property and agriculture fields. However, no human casualty was occurred in the same incidences. There has three toks namely Ropad Tok, Sirwakhan Tok and Lorkhet Tok which are comes under the Josha Village having NNW-SSE trending Bina-Martoli Dhar Ridge. These toks were observed to be located amid agricultural fields that are intervened by both rock outcrops and overburden. Lorkhet Tok is located uphill side to Ropad Tok and both are on the right flank of Dhanpaniyari Gad while Sirwakhan Tok is located West extremity to these toks and on the right flank of Dhol Gadhera. The slope in these affected areas is generally observed dip towards South at gentle to moderately steep angles.

The rock exposures of Lesser Himalayan limestones and slates are observed along the nala and road section. These are generally observed to strike NE-SW with moderate dips towards WNW. Other two prominent joints, of which one was observed to dip towards ESE at steep angles (65º/110º) and another was observed to strike ENE-WSW at vertical angles (90°/80°). The slopes around the area have gentle-moderate gradients whereas the overburden thickness, including weathered rock zone, is around 2 to 5 meters. This overburden material comprises of debris consisting of greyish brown, fine grained silty matrix with angular fragments of limestones and slates. A number of agricultural fields around the village is observed to be damaged due to toe and gully erosion by streams.

Subsidence and ground fissures that were observed to facilitate movement of huge slope mass around the Ropad Tok. This caused a number of houses completely damaged and destroyed. Overall, the angle of failure slope is observed to be around 25° and even more. The direction of the slope is observed to be towards Northwest. The ground fissures in the newly under construction road area are observed to be 1.5 to 3.5 meters long (Fig. 6a). The subsided material lying on gentle to moderate slopes has developed tension cracks which were trending from WNW-ENE and N-S on the same area and these are observed to be up to 50 cm wide and 0.5 - 1.5 meters deep indicating active soil movement (Fig. 6b).

Recommendations: Subsidence and ground fissures that were observed to facilitate movement of huge slope mass around the Ropad Tok caused 8 houses destroyed. It is therefore highly recommended that immediately rehabilitation of this tok is need to be required and the residents are therefore advised to stay away from the active subsidence zone, especially during heavy or prolonged rainfall. Benching and erection of appropriately designed retaining structures with firm foundation are required to be erected around the affected area of Lorkhet Tok for protecting the habitations and agricultural fields as well as bank of Dhanpaniyari Gad from stream erosion on its right bank. Channelizing the entire course of the Dhol Gadhera in steps together with banks protection. This would help in reducing the pace of the flow and thus arrest erosion in the agricultural fields as well as Sirwakhan Tok area.

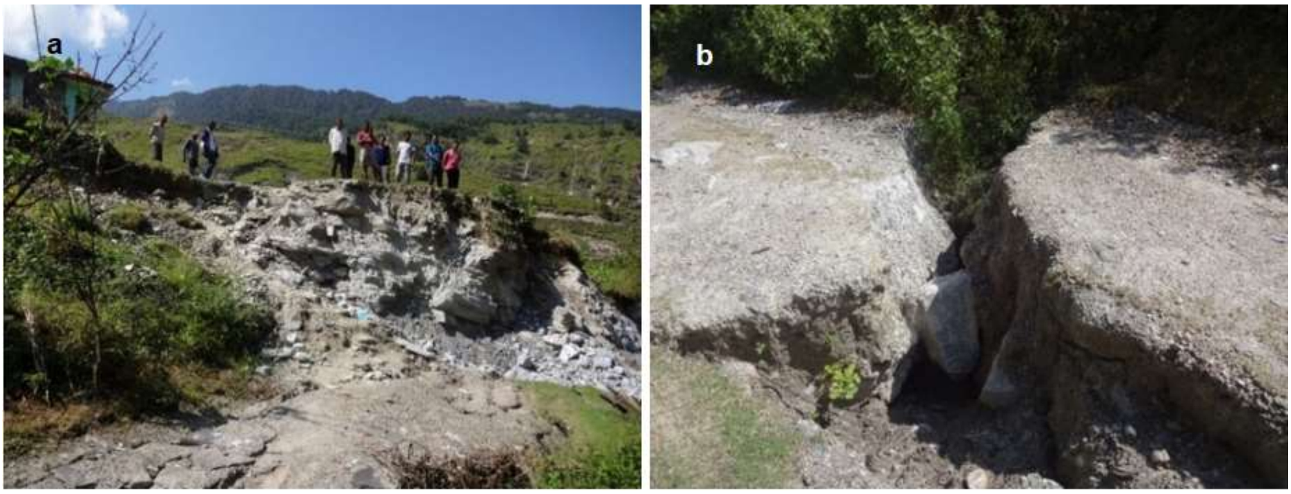

Fig. 6. Slope instability in the area around Josha Village; (a) ground fissures at Ropad Tok and (b) cracks trending N-S across newly under construction road between the Ropad Tok and Sirwakhan Tok area

4.4. Malupati (N 30°3'44.24" E 80°15'57.71")

Fresh ground fissure was observed to be occurred during the monsoon in the month of July 2020 after heavy rainfall at Malupati Village. Previously, there was a landslide occurred just below the village in years 2013, 2018 caused toe erosion by Bharadi Nadi. No human losses were however occurred because of the same events. Exposures of Lesser Himalayan limestones and calcareous slates are however observed upslope of village along the road section. These are generally observed to strike NW-SE with moderate dips towards SSW. Other one prominent joint was observed to dip towards ESE at steep angles (80°/80°). The rock exposers are not generally observed around the affected village. The same area is largely occupied by thick overburden material. Thickness of the overburden is observed to be around 6-8 meters. This material comprises of hill wash and debris that consists of grey to greyish brown, fine grained silty-clayey matrix with fragments and angular boulders of limestones and slates. The Failure slope is observed to have occurred on the Northwestern slope.

The ground fissures in the agricultural fields are observed to be up to 4.0 meters long (Fig. 7a). The subsided material lying on gentle to moderate slopes has developed tension cracks which was trending from NE-SW on the same area. Total of 2 houses were ruined in the same incidence (Fig.7b). As also, cracks were observed to be in a number of houses (Figs.7c and 7d).

Fig. 7. Ground subsidence related damages in the Malupati Village; (a) ground fissure in agricultural fields, (b) collapsed a house, (c) crack in a house and (d) detached back side wall of a house

Downhill slope of the village is observed to be affected by landslide. The same was occurred due to the toe erosion by the Bharadi Nadi on its right bank. The width of the failure slope is around 100 to 300 meters along the Northeast flowing Bharadi Nadi while the height of the slide from river bed to the crown is about 50-70 meters. The inclination of failure slope is observed to be around 35°. The Southeastern proximity to fresh ground fissure zone, a small seasonal stream is to be observed in the area. The same is flowing through the old landslide which was observed below the village area. Apart from, seepage was also observed in the agricultural fields between fresh landslide and old landslide in the area. Whole habitation of the Malupati Village is under high risk due to landslide and subsidence.

Recommendation: Presently, the Malupati Village is facing serious slope stability problem where whole habitated area is affected by active subsidence whereas downslope is affected by toe erosion of the Bharadi Nadi. These factors have critically affected the stability of the area. During investigations, wide cracks were observed in the walls and floors of many houses that indicating active slope movement in the area. It is therefore advisable to rehabilitate the Malupati Village to an alternate safe location.

4.5. Chana Tok (N 30° 5'24.05" E 80°15'33.48")

High velocity discharge through Dhapwa Gad due to heavy downpour occurred in the area around Serasuidhar Village on the month of July, 2020 caused damage to property and agriculture fields in the Chana Tok. The area around the tok was observed to have thick overburden and its thickness was up to 10 meters. This overburden materials comprised of hill wash and debris consisting of grayish brown to brown, fine grained silty-sandy matrix with fragments of gneisses and schists along with rare big boulders of gneisses.

No rock outcrop was observed in the vicinity of the tok. The exposures along the road section were however observed to be that of Chiplakot Crystalline schists. Rocks exposed in the area are generally observed to strike NE-SW with gentle dips towards NW. Other two prominent joints were observed to dip towards SE and E at steep angles (65°/130° and 70°/90°).

Toe erosion caused by spate in Dhapwa Gad during excessive rainfall events in this valley was observed to have contributed to the stability of the slopes in this area. The terraces of the tok were observed to be eroded by this stream. An eroded terrace having vertical slope at crown portion whereas moderately steep to steep slope between middle to toe portions with the slope direction being NNW. The width of the failure slope was about 50 meters and vertical height of the slide was from 15-20 meters. A house located just above the crown of this destabilized terrace was observed to be severally damaged and in highly vulnerable state (Figs. 8a and 8b). As also, slope failure was occurred on the opposite bank where numbers of trees were uprooted in the same incidences.

Recommendations: The house which was damaged severally by flooding of Dhapwa Gad is not found suitable for living. It is therefore highly recommended that immediately demolished the same and displaced the habitations at safer place. Further construction of house in the same must be prohibited in the area. At least 5 meters buffer zone to be kept from eroded terrace cut and construction of houses in the same zone should not be allowed. Appropriately designed retaining structures of suitable height with firm foundation are required to be erected on right bank along the affected area for checking the toe erosion by Dhapwa Gad. This would help in protecting the agricultural fields from further extension of slide at affected site as well as bank of Dhapwa Gad from stream erosion.

4.6. Tanga (N 30°1'4.92" E 80°19'48.77")

Heavy localized precipitation/cloudburst like incidence took place around Tanga Village on 20 July 2020 in early morning at 3:40 AM. This caused a number of superficial landslides which triggered in the area (Fig. 9a). Down pace movements of debris flow from the same landslides were adversely affected the area that result in enormous losses of human lives, animals, properties and agricultural fields.

Fig. 8. Severally damaged a house due to toe erosion by Dhapwa Gad; (a) on the edge of failure terrace and (b) close view of the same house

The area is bounded by two minor seasonal streams which are flowing from NW-SE having steep gradient. The slope in the area is generally observed dip towards Southwest at steep angles (50°-65°) having Northeast trending ridge. This has facilitated fast downslope movement of debris. The thickness of the debris accumulated in the area is observed to be around 1.0 to 2.0 meters. This material is observed to comprise of hill wash and debris consisting of brown, fine grained silty-clayey matrix with rare angular boulders and fragments of slates. The rock exposures of Lesser Himalayan slates are observed along the stream bed and are generally observed to strike NW-SE with gentle dips towards NE. Other two prominent joints, of which one was observed to dip towards ENE at very steep angles (85°/70°) and another was observed to strike ESE-WNW at vertical angles (90°/110°).

The Southwestern proximity to the village area, West flowing seasonal stream is observed to have overrun the agricultural fields and had create deep gullies in the area. This directly hit habitations of which some proximity to its course. As many as 11 persons lost their lives, of which one person was injured and body of one person could not be recovered together with 12 animals were lost in these incidences. A number of agricultural fields were also damaged and total of 4 houses were destroyed in these incidences (Fig. 9b).

The upslope of the Tanga area was triggered by many superficial landslides and downhill of the same was eroded by bank erosion of the Pena Gad during excessive rainfall events. This was observed to have contributed to the stability of the slopes in this area. An eroded terrace with sub-vertical cut around of 40-60 meters was observed on the right bank of Pena Gad just below the entire stretch of the village area indicating active movement in the area.

Recommendation: The upslope of the Tanga Village was triggered by many superficial landslides whereas the downhill movement of the upper crest all along the village due to toe erosion by Pena Gad indicates that active slope movements in the area. Therefore, no remedial measures will be sufficient considering the location and risk involved, hence permanent rehabilitation of the Tanga Village to safer location is recommended.

4.7. Choribagar Tok (N 29°56'35.64" E 80°18'6.85")

Bank erosion caused by spate in Goriganga River during excessive rainfall events on 20 July, 2020 in this valley was observed to have contributed to the stability of the terrace in Choribagar Tok of Bangapani Village. The area around the tok was observed to have thick overburden and its thickness was up to 7 meters. This overburden material was observed to comprise of river borne materials that consists of grey, medium grained sandy matrix with rounded boulders, cobbles and pebbles. The river terrace was observed to be cut vertically by Goriganga River. An eroded terrace with vertical cut around of 3-4 meters was observed on the left bank of the same. Total of 7 houses were destroyed and washed away in flooding of the same (Fig. 10a). The Goriganga River is observed to be shifted its course towards tok by 20 meters approximately due to excessive flood discharge in the river and has contributed to the erosion of the terrace.

A seasonal stream flowing from NW-SE direction was observed to flow above the road head through the agricultural fields and habitations of the tok (Fig. 10b). A number of agricultural fields were observed to be eroded by the same. This has removed the sediments and made deep gully as well as destroyed the houses which were located along its course.

Recommendations: A seasonal stream above the road area which has formed gullies in the agricultural fields of the tok. This stream should be properly channelized up to the Goriganga River. This would help in reducing further gully erosion by doing the same. Appropriately designed flood protection structures with firm foundation against suitable flood value are required to be erected for preventing toe/bank erosion by Goriganga River. This would help in protecting the agricultural terraces as well as bank of the same from bank erosion and hitting actions of large rolling boulders. At least 10 meters buffer zone to be kept from eroded terrace cut and construction of houses in the proximity to the affected site should not be allowed.

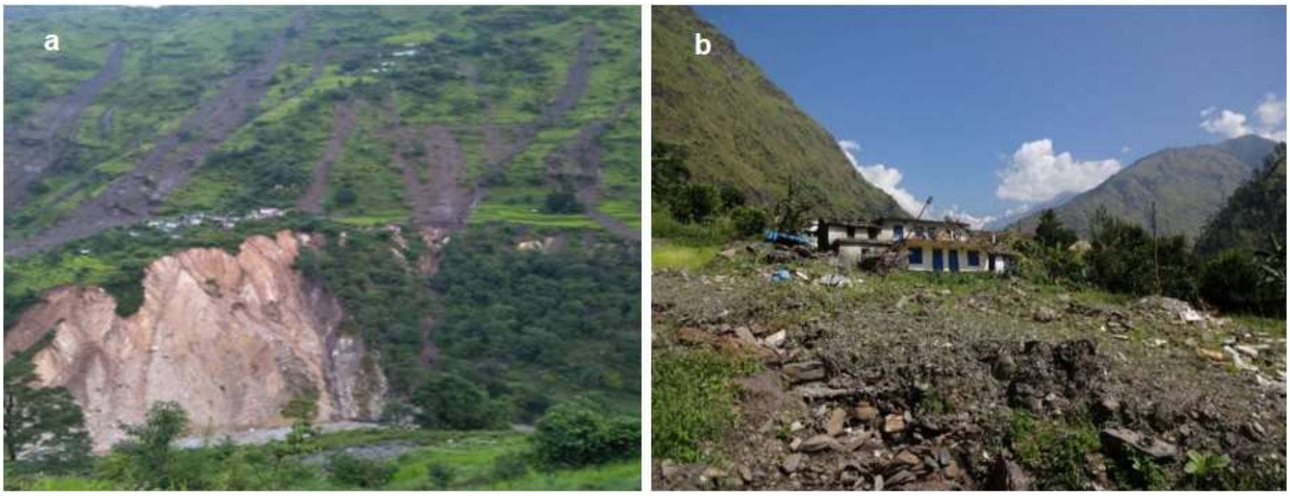

Fig. 9. Heavy rains triggered landslides and associated damages; (a) numbers of superficial landslides whereas downslope affected by Pena Gad and (b) the place where houses were destroyed along with casualties

4.8. Talla Mori Tok (N 29°54'22.02" E 80°18'43.37")

Excessive water saturated debris with huge boulders flowed down through the Mori Nala, which is flowing from E-W in the area and had occurred on July, 2020 in two phases. In 1st phase, huge debris with boulders flowed down through Mori nala after heavy rainfall in the early morning at 5:30 AM. In this incidence 3 shops were washed away and Munsiyari-Joljibi Road was overrun. Apart from huge sediments with boulders which had been transported by the Mori nala, deposited all along the main course and blocked the same (Fig. 11a). In 2nd phase, huge debris with boulders flowed down through Mori nala which had happened after 20 minutes of 1st phase event. This completely changed the course of Mori Nala towards SW direction where to the downstream side the habitations of Tall Mori Tok of Bangapani Village are situated on the river born materials terraces. In this incidence 11 houses were destroyed while 15 houses were severally damaged (Fig. 11b). Apart from, a number of agricultural fields of this tok were also damaged and filled with debris and big boulders (2-3m dia.). The thickness of debris with boulders is to be observed around 2.0 to 5.0 meters at the site.

Previously, this tok was affected by flooding of the Goriganaga River in June 2013. These caused around 13 houses and 17 families were in the risk apart from around 350 Nali agricultural fields were lost in these incidences (Bishwapriya et al., 2013).

Recommendation: The erosion action of both Goriganga River and Mori Nala contributed to the stability of the Talla Mori Tok. Settlements of Talla Mori Tok had already been affected by flooding of Goriganga River and Mori Nala. Because of the same this area is highly vulnerable to flooding further it is not economical to clear the deposited debris in the whole area and will create future threats to tok particularly during monsoon. It is therefore advisable to shift the entire tok to an alternate safe location.

4.9. Gela Malla Tok (N 30°4'29.13" E 80°19'30.882")

Newly under construction road valley side slope triggered after heavy rainfall of 20th July, 2020 at Gaila Malla Tok in Pattharkot Village of Bangapani Tahsil. Debris slide is observed to have occurred on the West slope of tok. The inclination of failure slope is observed to be 60°-70°.The width of the failure slope (damaged road section) is about 40-50 meters at the crown portion and height between toe and the crown is about 55-65 meters (Figs.12a and 12b). Thick pile of loose debris along with wire crates retaining structures that descended down from the area upslope of the tok is observed to have badly hit both agricultural fields and a house. As many as 3 persons of a family lost their lives in the same incidence. As also, the South proximity to the failure slope just below road area, there is a wire creates retaining structure which was observed to be partially bulged and tilted. The same is posing risk to a house which is located downhill of its.

Recommendations: The road should be shifted towards hillside along the affected slide zone. After this suitably designed breast wall of appropriate height with weep holes should be constructed at road level. In case of South proximity to slope failure zone, tilted and bulged wire creates retaining structures should be reconstructed properly with due attention to actual ground conditions. It is also strongly recommended that construction of any sort should not be allowed around the affected zone. The households located below the same zone are required to be shifted to alternate safer locations.

Fig. 10. Bank erosion and gully erosion related damages in Choribagar Tok; (a) eroded terrace with destroyed houses and (b) eroded agricultural fields by local stream

Fig. 11. Flooding of Mori Gad and associated damages; (a) deposited sediments and diverted the flow of Mori Gad and (b) destroyed houses and partially damaged houses along with agricultural fields filled with sediments

Fig. 12. Slope failure at Gaila Malla Tok in Pattharkot Village; (a) failure slope above destroyed house (b) damaged portion of under construction road

Fig. 13. Severally damaged a house in Khetali Village located in close proximity to eroded terrace cut that was eroded by Barar Gad

Fig. 14. View of eroded terrace with houses in vulnerable state on the left bank of Barar Gad; (a) panoramic view and (b) close view

4.10. Khetali (N 29°55’35.10” E 80°14’14.22”)

High velocity discharge through Barar Gad due to heavy rains occurred in the area around Khetali Village on the month of July, 2020 caused a double storied house was severally damaged. The failure slope in right portion of the house is observed to have occurred on the Southwestern slope having almost sub-vertical to vertical due to heavy rainfall associated with gully erosion, underground seepage and toe erosion by Barar Gad on its right bank. The width of the eroded slope is about 120 meters along the stream and height of the slope is about 60-70 meters (Fig. 13). Right portion of this house and a track were damaged in these incidences.

Mostly, rock exposures of limestones of Lesser Himalaya were observed to be highly weathered having with caves and calcite leaching along the road section just above the affected area. The bedding plane in limestones is generally observed to be well developed at places upslope side of Tok along road section and dips at 65° towards Northwest direction. The rocks in the area are traversed by two important joint sets that are observed to dip at moderate to steep angles towards SSW and SE (60º/220º and 35°/150°). Dhami Gaon-Barah Motor Road is going on just upslope of the village area whereas 2 depressions were observed during field investigations, one is just right side to the affected house portion and another is on the left side to the same house. Both are creating risk to the area, particularly during the rainfall. Apart from, road side drain was chocked with debris and has not sufficient to carry monsoonal discharge.

Recommendations: The house near the slide area should be demolished and people must be made aware not to construct any habitat in and around the slide area. At least 5 meters buffer zone to be kept from eroded terrace cut and construction of houses in the proximity to the affected site should not be allowed. Road side drain should be lined with suitable gradient and connected it with nearest depression/ streams. This would protect the houses from down thrust of the monsoon discharge. The affected slope to be retained must be protected by wire mesh along with hydroseeding. As also, a toe wall along the Barar Gad in the whole length of the affected village should be provided in order to check the toe erosion and the scouring action in this area.

Fig. 15. Slope instability and associated damages in the Gat Tok; (a) ground fissures zone, (b) destroyed a house, (c) cracks on floor and wall of a house and (d) cracks on front portion wall of a house

4.11. Khetbharar (N 29°55’35.87” E 80°13’56.13”)

High discharge of Barar Gad during excessive rainfall events in the month of July, 2020 is deduced to have contributed to the stability of the slopes in the Khetbharar area. The terrace is observed to be cut vertically by this Gad on its left bank where the habitations of this village is situated. An eroded terrace with vertical cut of around 20 meters is observed on upstream of motor bridge on the left bank of Gad while around 1.0-3.0 meters terrace cut towards downstream of Bridge with a number of damaged structures (Figs. 14a and 14b). In which some structures were severally damaged whereas some were washed away in flooding of Barar Gad. The main settlement is observed to be located over river borne materials terrace in proximity of the Barar Gad. The spate in Gad has eroded the terrace on its left bank and has severely damaged the three buildings, as also numbers of agricultural fields just upstream of Bridge. Public toilet and a house were washed away along with a house was severally damaged and also safety walls of Panchayat Ghar as well as Government Intermediate Collage were damaged on the downstream of the Bridge. In this area, the Gad has eroded around 15-20 meters towards the left bank upstream of motor Bridge.

Recommendations: In order to protect the eroded terrace cut and vulnerable constructions, a suitably designed protection wall should be constructed with firm foundation. This would protect the terrace as well as bank of Barar Gad from stream erosion. No further construction should also be allowed in this zone. Similarly, slopes in the downstream should be stabilized with suitably designed retaining walls all along the banks of Barar Gad, in order to protect the Panchayat Ghar and Government Intermediate Collage.

Fig. 16. Damages during rainfall in Dhami Tok; (a) Gully erosion by seasonal nala and (b) the ground fissures in the agricultural fields at Dhanari

4.12. Gat Tok (N 29°55'5.86" E 80°9'29.124")

Ground fissures was taken place after excessive rainfall in the month of July, 2020 caused property damages in the Gat Tok of Gatghorgari Village. This Tok is bounded by streams like Hardiya Nala and Ramganga River which are flowing respectively in West and Southeast directions in this region. Thinly to medium bedded and fragile nature of the limestones and slates together with overburden has resulted in the formation of landslide that is observed to facilitate movement of huge slope mass uphill and downhill side to the tok. The direction of the slope is observed to be towards West.

Mostly, exposures of Lesser Himalayan dolomitic limestones with intercalation of slates were observed on the upslope side of the tok as also along the road section. However, a bend of quartzites was also observed at Hardiya Nala new landslide zone along the road section. The general trend of the rocks was observed to be E-W with moderate dips. The bedding plane was generally observed to be well developed and dips at angles 45° towards Due North. The joint sets were observed to have moderately steep to steep dips towards SSE and SW respectively (55°/160° and 65°/240°).

The ground fissures in the failure slope area are observed to be 1 to 3 meters long (Fig. 15a). The subsided materials lying on gentle to moderate slopes has developed tension cracks which was trending from NNW-SSE on the cultivated lands and these are observed to be up to 50 cm wide and 1.0-2.0 meters deep indicating active soil movement. A double storied house was destroyed because of the subsidence in the same area (Fig. 15b). Apart from, cracks were observed to be in 3 houses which are situated in South proximity to slope failure and subsidised zone (Figs.15c and 15d).

Recommendations: Landslides are observed to occur uncontrollably over the entire stretch of the Gat Tok because of the erosion by Hardiya Nala and toe cutting by road. These pose threats to the houses located on the same. In view of high vulnerability to massive landslide, it is highly recommended that construction of any sort should not be allowed around the slide zone. The households located around the landslide zone are required to be shifted to alternate safer locations. However, the protection/mitigation works along the Hardiya Nala landslide zone where leading Munsiyari-Nachani Road must be taken up for ensuring safety of human being and proper connectivity.

4.13. Dhami Tok (N 29°51'19.30" E 80°29'29.91")

Heavy rainfall occurred on 27 July, 2020 caused a number of agricultural fields were damaged together with foot track. However, no losses of lives and property damages were occurred in the Dhami Tok of Galati Village. A small seasonal nala is to be observed between habitations of the tok which is flowing from NW-SE direction having steep gradient (60°-70°). The thickness of overburden in the same area is observed to be around 1.0-3.0 meters. This material is observed to comprise of hill wash and debris consisting of brown, fine grained silty-clayey matrix with rare angular boulders and fragments of slates. During heavy rainfall, water saturated debris flowed down through this nala which had made deep gullies (around 2-3 meters deep and 3-4 meters wide) and damage to a number of agricultural fields located along its course (Fig. 16a).

Mostly, exposures of Lesser Himalayan slates were observed on the upslope side of the village as also along the road section. However, boulders of tuffeceous rocks were also observed at Dhanari subsidence zone along the foot track section. The bedding plane was generally observed to be well developed and dips at angles 30° towards northeast. The joint sets were observed to have steep to sub-vertical dips towards SW and SE respectively (75°/240° and 85°/130°). The ground fissures in the agriculture fields are observed to be up to 3.0 meters long at Dhanari in Sarwa Dhar area (Fig. 16b). Around 50 meters foot track stretch was also completely damaged in the same place. The subsided materials lying on gentle to moderate slopes having with numbers of tilted trees which indicating active soil movement. The failure slope is observed to have occurred on the ESE slope. The overburden thickness is observed to be more than 8.0 meters in the same area. This material is observed to comprise of hill wash and debris consisting of brown, fine grained silty-clayey matrix with rare boulders of limestone/tufaceous rocks and fragments of slates.

Fig. 17. Cracks in houses of Khela Village due to creep movement; (a) cracks in house at Ala Tok, (b) severally damaged house at Kolpani Tok, (c) damaged right-side wall of traditional house at Chetkala Tok and (d) cracks on roof column and wall of primary school at Chetkala Tok

Recommendations: In case of a small seasonal nala, check dams with wire crates along the nala course should be placed for checking stream erosion in the area. The toe of the Dhanari ground fissures zone should be protected by appropriately designed retaining structures. This will protect the movement of critical slope mass in the area. It is also required that anthropogenic intervention of all kinds be strictly regulated in the proximity of seasonal nala and ground fissures zone. So, the villagers are advised to stay away from these places, particularly during heavy rainfall.

4.14. Khela (N 29°57'57.51" E 80°35'28.80")

According to local inhabitants, uncontrolled blasting for new road construction on the opposite hill slope has adversely affected the slope mass in the area. Creep movement was observed in the village which was noted during field investigations caused cracks on a number of houses. There has three toks namely Chetkala, Kolpani and Ala which are comes under the Khela village. Kolpani Tok is located just above the Ala Tok while Chetkala Tok is located North proximity to Kolpani Tok. The slopes in these affected areas are generally observed dip towards ESE at gentle to moderately steep angles. The slopes around the toks were observed to have gentle gradient because of step farming.

Mostly, exposures of Chiplakot crystalline gneisses were observed along the footpath section to the Northern extremity of the village and as also along the road section. General trend of the rocks was NW-SE and these were observed to dip towards Northeast at moderately steep angles

(40º to 45º). The rocks were observed to be traversed by numerous joints. These joint sets were observed to have steep dips towards S and NE respectively (65º/180º and 70º/60º).

These toks were observed to be located amid agricultural fields that are intervened by both rock outcrops and overburden. The entire area of the village was occupied by unconsolidated overburden mass comprising of grayish brown silty soil with rare big boulders and fragments of gneisses. Generally, overburden thickness including weathered rock zone was around 2-3 meters but at places thickness was observed to be as much as 5 meters during the field investigations. Cracks were observed in most of the houses of Chetkala tok, Kolpani Tok and Ala Tok (Fig. 17). These were attributed to active slope movement with local settlements of the loose overburden material.

Fig. 18. Damaged structures in Gwalgaon due to subsidence in loose debris materials during heavy rainfall; (a) scoring foundation of a house, (b) hanging foundation of a house in ground fissures zone, (c) damaged house over completely subsided loose debris mass and (d) a toilet was subsided in loose debris mass and deep sink hole was formed

Recommendations: Cracks were observed in the most of the houses that indicating active slope movement in the area. The hill slope around Khela Village is deduced to be highly susceptible to failure, particularly in the event of heavy or prolonged rainfall. The residents are therefore advised to stay away from the active creeping zone, especially during heavy or prolonged rainfall. The households of the all three toks are required to be shifted to alternate safer locations. Cracks on floor, roof column and walls of primary school at Chetkala Tok are indicating major settlements in the ground. It is highly recommended that the Primary School located in active creep zone be vacated and put to disuse immediately.

4.15. Gwalgaon (N 29°51'6.1632" E 80°32'30.6168")

A portion of the habitated area of Gwalgaon in Dharchula Town, subsided in the month of July, 2020 because of heavy rainfall in the area. Slope around this area is observed to have steep gradients with thick pile of overburden materials. Ground fissures in the habitated cut slope are observed to be around 4-5 meters long. Vertical height and width of the failure slope is around 15-20 meters and 40-50 meters respectively. 3 houses were damaged in this incidence of which foundations of 2 houses were hanging whereas a house was completely subsided and ruined (Figs. 18a to 18c). Apart from this a toilet was subsided in loose debris mass and deep pit was formed in that place (Fig. 18d). It is indicating that sink holes had formed in limestone/tuffacious rocks due to water action causing subsidence in ground at the same place. The affected area is observed to exhibit gentle slope because of step terracing and limestone/tuffaceous rocks is observed to constitute the bedrock just below the subsided area along the footpath section. Apart from, a shallow landslide was also occurred on Northern extremity to subsidence zone resulting in 2 water tanks damaged in these incidences. These tanks were also tilted due to local settlements. Another slope failure was occurred on Southern proximity to subside zone resulting in a house was badly damaged. Seepages and leakages were also observed in the same area because of improper drainage network.

Recommendations: Severally damaged houses and other construction works undertaken earlier in the affected zone should necessarily be dismantled and these areas be kept free of encroachment. The households of the affected areas are also required to be shifted to alternate safer locations. In view of future threats to Dharchula Town by this landslide, following mitigation measures are proposed to check the onward movements of slope mass. These are (a) re-profiling of affected slopes in the form of benches; (b) protection of slopes by geo-jute/geo-grid; (c) stepped breast walls with weep holes towards hill side and (d) Channelizing of the seepages and leakages with proper drainage arrangements. It is advisable that aforesaid mitigation measures must be incorporated after detailed plan of the affected subsidence and landslide zones and relevant field geotechnical investigations.

5. Discussion and Conclusion

In Monsoon 2020, the villages of Tejam, Munsiyari, Bangapani and Dharchula Tehsils of Pithorgarh District cover under the present investigations were observed to face serious slope instability. The same attributed to heavy precipitation received between 19th and 20th as well as 28th and 29th in the month of July, 2020 in the Munsiyari and Dharchula Tehsils. Most of the incidences were happened in many parts of the same regions on these days. Rains added discharge of rivers and their tributaries which triggered landslides at many places due to toe/bank erosion and as a consequence damaging some of the habitations badly. Additionally, vehicular traffic, electricity and drinking water facilities were also damaged and disrupted. The worst affected habitations of Tanga and Gaila Malla Tok of Pattharkot Villages in terms of loss of human lives.

Geologically the rocks belong to Central Crystalline and Lesser Himalaya are exposed in the present study region. The major tectonic discontinuity MCT separates the rocks of Central Crystalline Group from underlying Lesser Himalayan Garhwal Group and Chiplakot Crystalline of rocks laying south of its. This made the rocks of the area highly fragile, jointed, folded and fractured.

The main factors responsible for slope instability and mass movements are excessive heavy rains, heavy localized precipitation/cloudburst, hillside slope cutting for road widening, unplanned debris disposal, toe/bank erosion by streams/rivers, encroachments over seasonal streams, and heavy construction over loose soils, and habitation located bottom of high hills, and habitation situated over flood plains. Amongst these are mainly responsible for damages in the villages. Based on the preliminary geological-geotechnical assessments of the specific landslide affected sites, causes of slope instability and appropriate mitigation measures/ suggestive measures have been recommended in the previous sections. In order to be effective, all the slope stability related measures must be incorporated under the supervision of experienced geotechnical engineer/civil engineer. The suggested mitigation measures would help in reducing the vulnerability of the affected villages and provide stability to the slopes. However, the possibility of these being reactivated by extreme precipitation events and high intensity seismic tremors cannot be ruled out. The villages that were identified as highly vulnerable state because of slope instability are not found suitable for mitigation and habitation purpose. It is therefore recommended that the same be relocated at alternate safer places. The residents of the affected villages are advised to stay away from highly unstable slopes and take necessary precautions, particularly during the rains.

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