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Geomorphic Threshold and Landsliding in Paglajhora Sinking Zone, Darjiling Himalaya

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Abstract: *Assessment of geomorphic threshold is a significant parameter in landslide studies. The present study dealt with critical slope angle (c_φ), critical rainfall (c_r) and critical height (c_h) of the Paglajhora Sinking Zone. This sinking zone is located in the representative mountain watershed, the Shiv-khola of Darjiling Himalaya, West Bengal. To estimate critical slope angle (c_φ), a Mohr stress Diagram was developed using tri-axial compression test parameters such as cohesion (c), major principal stress (σ_1) and minor principal stress (σ_3). Thickness of total soil (h), thickness of saturated soil (z), wet soil density (Ps), density of water (Pw) angle of repose (ϕ) and slope on scar face (θ) were assessed study the stability condition of the hill slope. The directional slope length and effective contour length were taken into account to determine upslope contributing area and critical rainfall (c_r) of major landslide locations. The critical height (c_h) was derived for the initiation of landslips incorporating cohesion (c), angle of internal friction (ϕ), unit weight of materials (γ) and slope angle (θ).*

Keywords: *Paglajhora Sinking Zone, Critical slope, critical height and critical rainfall and geomorphic thresholds.*

1. INTRODUCTION

Geomorphic threshold is significant parameters in analyzing the stability condition of particular spatial unit in a quantitative way. According to White et al., (1996) 'the minimum or maximum level of some quantity needed for a process to take place or a state to change is generally defined as threshold. Varnes (1978) studied the role of minimum intensity and duration of rainfall to cause a landslide of shallow soil slips, debris flows, debris slides or slumps. Crozier (1997) opined a maximum threshold, beyond which there is 100% chances of occurrences of the process at any time when the threshold value is exceeded. The most commonly investigated threshold parameters such as critical slope, critical slope height and critical rainfall (cumulative rainfall, antecedent rainfall, intensity and duration of rainfall) in relation to landslide phenomena has been attempted to identify in the present study. Starkel (1972) for the first time, observed the geomorphic effects of an extreme rainfall event in the eastern Himalaya (Darjiling), India. Froehlich et al., (1990) investigated the same area and found that shallow slides and slumps on steep slope segments occur when 24 hours rainfall reaches 130-150 mm or continuous three days rainfall totals 180-200 mm. Campbell, 1975; Cotecchia, 1978; Caine, 1980; Innes, 1983; Pomeroy, 1984; Canon and Ellen, 1985; Keefer et al., 1987; Kim et al., 1991; Li and Wang, 1992; Larsen and Simon, 1993; Wilson et al., 1995; Wieczorek, 1987, 1996, 2000; Terlien, 1997, 1998; Crosta, 1998; Crozier, 1999; Glade et al., 2000; Aleotti, 2004; Guzzetti et al., 2004, 2007; Hong et al., 2005; and Zezere et al., 2005 tried to establish rainfall-intensity thresholds for predicting the slope failure accurately. Caine (1980) first established worldwide rainfall threshold values for landslides. Montgomery and Dietrich (1994) introduced a physically based model for the topographic control on shallow landsliding in terms of geomorphic threshold. Recently Guzzetti et al., (2007) reviewed rainfall thresholds for the initiation of landslides worldwide and proposed new empirical thresholds based on the statistical analysis of the relationship between rainfall and landslide occurrences. They defined intensity-duration threshold as:

$I=73.90D^{-0.79}$ ……………………… (1).

Where, I is the hourly rainfall intensity in millimeters (mm hr-1) and D is duration in hours.

Brunsden et al., 1981; Wagner 1983; Manandhar and Khanal, 1988; Dhital et al., 1993; Upreti and Dhital, 1996; Gerrard and Gardner, 2000; Dhital, 2003; Dahal et al. 2006a, while other works, such as Caine and Mool (1983), and Dhakal et al. (1999) focused mainly on landslide risk assessment in Himalayan terrains by analyzing physical properties of landslides and debris flows, effects of regional and local geological settings, and recommendations for environmental-friendly preventive measures.

Figure1. *Location of Paglajhora Sinking Zone in Darjiling District*.

In the Shivkhola watershed, the physical processes and human actions (formation of road-cut benches and concentration of human settlement) are active on the slope in a systematic interactive combination by anthropogenic processes which make the slope steeper than repose angle varying from 19^0 to 23^0 with an average of 21^0 and thus the instability is introduced into the system. The present study attempts to identify/determine the critical values of rainfall, slope height and slope angle beyond which there is a greater probability of slope instability in Pglajhora sinking zone of the Shivkhola Watershed (Figure1). The formation of road-cut benches to develop communication network lengthens the steep slope, removes the lateral and basal support, and disturbs the soil, favours infiltration and through-flow, helping in the increase of wet soil depth. All those change and their combined manifold after-effects help to generate geomorphic threshold and the shear stress to increase over shear strength. Sometimes, moderate levels of rainfall for few days in the basin become more critical because of weak lithological composition. Moreover, the concentration of human settlement and development of communication lines generates enormous pressure on slope materials and favours threshold values by reducing the shearing strength. The study shows that only 88.928mm daily rainfall is the critical rain for initiation of slide at Paglajhora. So there is every possibility for the generation of geomorphic threshold for initiation of slide due to hydrologic factor. In this way, there is a frequent occurrence of debris slide which reduces the slope angle on landslide scar face to that of repose angle to attain temporary stability through internal feed back in a process of homeostatic adjustment.

Study involves the measurement of upslope contributing area, contour length, slope angle, transmissivity, depth of soil, depth of the saturated soil, density of water, wet soil density, unit weight of the materials, pore-water pressure, cohesion, and angle of repose for the determination of 'intrinsic threshold' (Schumm,1977) condition such as critical slope angle, critical rainfall and critical slope height beyond which slope materials may undergo chemical decomposition and thereby lose its former strength and the slope may collapse without an extrinsic type of threshold being crossed. The response to threshold crossing may induce dramatic erosion and striking changes of the concerned landforms which is shaped primarily by the disturbances rather than by normal events. The recoveries of such disturbances are often a long and slow process which is mainly accomplished through Self-organized Feed Back Mechanism in the geomorphic system.

- Mallet opined (1874), in the Darjeeling territory the "Gondwana" rocks are overlain by the metamorphic rocks, which are termed as "Darjeeling Geniss" (mainly mica-gneisses and Schists) and "Daling" (mainly slates and phyllites). Darjiling gneiss and Chungtang formation (upper part of Daling) aer associated basically covered the Paglajhora Sinking area. These two lithological units composed of highly foliated gneiss, mica-schists and occasional bands of flaggy quartzites and granulitic rocks, slates phyllites with occasional quartzite, quartz-schists and greywake schists (Figure 2)

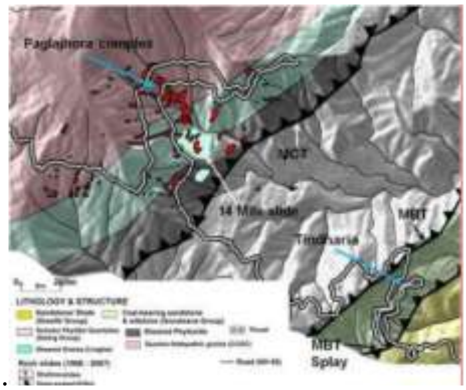

Figure2. *Location of Paglajhora with lthology and structure (Ghosh et al. GSI***)**

mylonitised granite with sub-parallel thrust**,** phyllite, silvery-mica-chlorite-schist, grey sericite, and Slate phyllite with quartzite, quartz-schist & greywake schist. The zone is characterized by the following structurally controlled phenomena.

- Seepage through heavily disintegrated and decomposed materials and formation of clay minerals, which induces slope instability.
- Rocks are traversed by quartz and quartzo-felspathic veins and the rocks are often highly metamorphosed and jointed.
- Recrystallisation and cataclastic deformation have destroyed the clastic texture with intense granulation along narrow zones of fracture.
- The apexes of the sliding zones are predominated with good amount of organic matter which encourages high water holding capacity and volume expansion.
- The apexes of the sliding zones are deforested and are susceptible to both sheet and gully erosion.

In the Paglajhora Sinking zone the heavily disintegrated fragile lithology makes the slope more vulnerable to landslip. Starkel (1972) for the first time, observed the geomorphic effects of an extreme rainfall event in the eastern Himalaya (Darjiling), India. Froehlich et al., (1990) investigated the same area and found that shallow slides and slumps on steep slope segments occur when 24 hours rainfall reaches 130-150 mm or continuous three days rainfall totals 180-200 mm.

Plate1. *Destructive failure in Paglajhor Sinking Zone (1998),* **Plate2.** *Destruction of toy train at Paglajhora*
from the main slide (September, 2002)

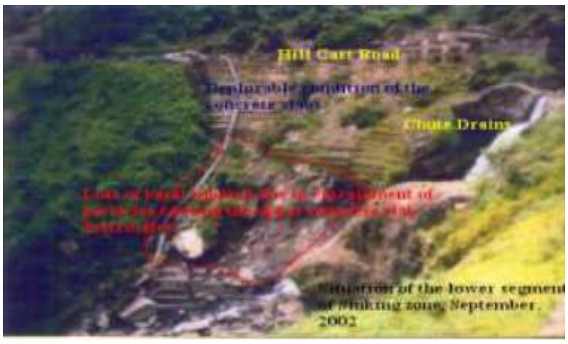

Plate3. *Downslope subsidence in 2002.* **Plate4.** *Fresh landslides in Paglajhora (2002).*

Plate5. *Road side failure at Paglajhora (2009)* **Plate6**. *A complete distruction in paglajhora(2011)*

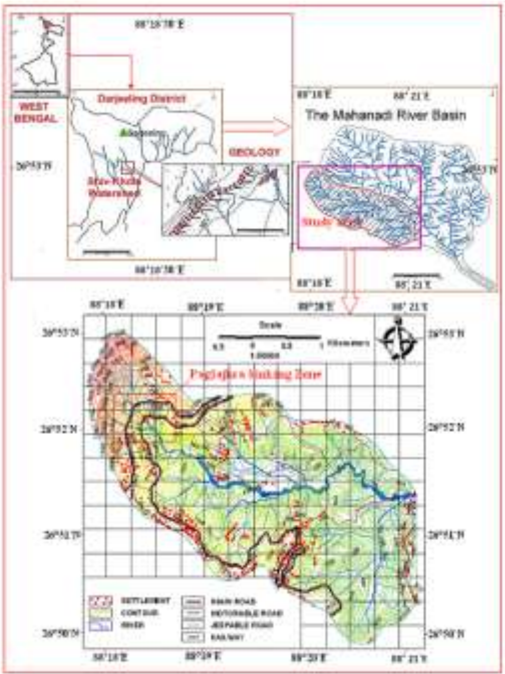

Figure5. *Location of Paglajhor Sinking Zone in the Shivkhola watershed.*

Figure4. *Landslide in June, 2015 at Paglajhora.* *Figure 4: View Landslide in June, 2015 at Paglajhora.*

2. MATERIALS AND METHOD

2.1. Determination of Angle of internal friction (φ) and Cohesion (c) and Transmissivity (T)

The geo-technical factor like angle of repose of the debris is measured after Bloom (1991) and Pethick (1984). The tangent of angle of repose of dry granular materials is slightly greater than, but approximately equals to the co-efficient of sliding friction of the material or its mass friction (ϕ) (Van Burkalow, 1945 and Bloom, 1991). The cohesion and angle of internal friction is measured by tri-axial compression test following Mohr stress Diagram. Major Principal Stress and minor principal stress were measured from GSI Soil Laboratory to estimate cohesion and friction angle. A Mohr Stress Circle was developed to obtain angle of internal friction and angle of rupture through σ_3 and σ_1 with the centre on the horizontal axis; the centre of the circle was obviously $(\sigma_1 + \sigma_3)/2$ and the radius was $(\sigma_1 - \sigma_3)/2$. The values of confining pressure, σ_3, and compressive stress, σ_1 were plotted on horizontal axis where stress difference is $\sigma_1 - \sigma_3$. On a plane parallel to the greatest principal stress axis (2α=0) the normal stress across the plane was σ_3 and the shearing stress was 0. If the plane makes an angle of 45^0 with the greatest principal stress axis (2α=90), the shearing stress is at a maximum and the normal stress is $(\sigma_1 + \sigma_3)/2$. If the plane makes an angle of 90^0 with the greatest principal stress axis ($2\sigma = 180^0$), the shearing stress is 0 and the normal stress is σ_1.

In this way a series of experiments were being accomplished with different values of confining pressure (σ_3). The Mohr Circle shows that as the confining pressure is increased, the stress as well as the stress difference must be increased to produce rapture. A line which is the tangent of the *'Mohr Circle'* is called as the *'Mohr Envelope'*. The angle that this line makes with the horizontal axis of the diagram is the angle of internal friction, φ. The saturated conductivity of the sail varies from 10^{-2} m s^{-1} for the soil depth less than 0.5m to 10^{-5} m s^{-1} for soil depth between 1 to 2 m (Fenti, 1992). Based on these and other data, Matteotti (1996) estimated the transmissivity (T) of saturated soil to lie between 5 and 30 m^{-2} day $^{-1}$, with a mean value of 15 m^{-2} day $^{-1}$ (Borga et.al 1998) and considering the mean value of transmissivity (T) threshold parameters were assessed.

2.2. Determination of Threshold Slope Angle for Initiation of Slide

The formation of road-cut benches introduces the steep back slope and the slope on the landslide scar is greater than the angle of repose. This situation is mainly responsible for instability. The stability equation for a mass of loose, friable cohesion less debris after Melnikov and Chesnokov (1969) is as following.

$$\text{Safety Factor} = \frac{\text{Shear Stress}}{\text{Shear Strength}} = \frac{W \cos\theta \tan\phi}{W \sin\theta} \geq 1 \quad \text{(eq.2)}$$

or, $\dfrac{Tan\,\phi}{Tan\,\theta} \geq 1$

or, $\phi \geq \theta$ -- (eq.3)

2.3. i.e.[(Angle of Repose/Angle of Internal Friction) ≥ (Slope on scar face)]

Where, Tan ϕ = Co-efficient of friction; φ= Angle of repose; W = Weight of Soil and θ = Slope on Scar face.

The average slope angle of Paglajhora is $53^0 20^{\prime\prime}$ which always outweighs the angle of repose. The other indefinite slope stability model for cohesion less material and slope parallel seepage after (Borga et. al. 1998) also supports the equation 4.

$$\frac{h}{z} = \frac{Ps}{Pw}\left(1 - \frac{Tan\,\theta}{Tan\,\phi}\right) > 1 \quad \text{(eq.4)}$$

Where, h=Thickness of Total Soil; z=Thickness of Saturated Soil; Ps=Wet Soil Density; Pw= Density of Water; ϕ=Angle of Repose; and θ=Slope on Scar Face.For maintaining the stability 'h' is needed to be greater than 'z' and $\left(1-\frac{Tan\theta}{Tan\phi}\right)$ should be positive.

So $\left(1-\frac{Tan\theta}{Tan\phi}\right)$ ----------------------------------- (eq.5)

Or, $\left(1\geq\frac{Tan\theta}{Tan\phi}\right)$

Or, $Tan\phi \geq Tan\theta$ Or $\phi \geq \theta$ ------------------------------------ (eq.6)

(Angle of Repose) ≥ (Slope on Scar face).

3. Saturated Soil Depth

The depth of the failure surface was measured by holding a measuring tape at both the margins of scar and the other tape was allowed to hang, the reading was then taken from the base of the hanging tape. The margin of the scars was surveyed by *prismatic compass*. The intensive survey of the sliding scar for 50 different landslide locations was carried on by *Abney's level* at 0.5m interval along radial lines originating from lower most part of the scar. The altitude of the points at 0.5m interval along the radial lines is then estimated using Sine rule in reference to the central base point of known altitude determined by GPS (Basu and Maiti, 2001 and Maiti, 2007). The total thickness of soil and that of saturated soil for 50 sites during monsoon were measured from slope cutting. After estimating the approximate depth of all known points, a soil depth map (z/D) was made using Arc GIS tool.

3.1 Unit weight of the soil (W), Wet soil density (Ps) and density of water (Pw)

The unit weight of the soil (W), Wet Soil Density (Ps), Density of Water (Pw) were estimated following 'Keen Box Methods' and examining the soil samples collected from 50 landslide locations in the study area. Specific unit weight of water and unit weight of the soil were estimated by examining the soil samples collected from 50 landslide locations during field investigation from the GSI (Geological Survey of India, East Kolkata) laboratory. The density of soil and water varies from place to place due to in situ geo-hydrologic condition.

3.2 Upslope Contributing area (uca)

Upslope Contributing Area (UCA) is an effective indicator of drainage concentration over space. The place having more contributing area encompasses more soil saturation and reduces soil cohesion. The specific contributing area (total contributing area divided by the contour length) is computed by distributing flow from a pixel among its entire lower elevation neighbour pixel (Borga et.al., 1998). Quinn *et al.* (1991) proposed that the Fraction of Flow (F_i) allocated to each lower neighbour (i) is determined by using equation-1.

An upslope contributing area map was prepared based on calculated contributing area value for each (0.25 sq.km) grid and it was divided into 6 equal classes.

$Fi = \frac{\mathrm{SiLi}}{\Sigma\mathrm{SiLi}}$ --------------------------------------- (eq.7)

[Where, the summation (Σ) is for the entire lower neighbor, S is the directional slope, and L is an effective contour length that acts as the weighting factor. The value of L used here is 10 m of the pixel size of the cardinal neighbour and 14.14 m of the pixel diagonal for diagonal neighbor].

3.3 Threshold rainfall to initiate landslip

Campbell, 1975; Caine, 1980; Larsen and Simon, 1993 established that the empirical threshold condition to initiate landslide refers to relational value based on statistical analysis of the relationship between rainfall and landslide occurrences where as the physical thresholds are usually determined with the help of hydrologic and stability models that take into consideration of various attributes such as transmissivity (T), wet soil density (p_s), density of water (p_w), slope angle (θ), angle of internal friction (ϕ), relation between rainfall and pore-water pressure etc. In the absolutely unstable condition the role of rainwater to initiate the threshold for sliding could be determined. If the hydrological factors like rain fall and seepage flow are considered the threshold condition for absolute instability can be predicted. The critical rainfall (r_{cr}) after Borga et.al. 1998 following equation no 8.

$$r_{cr} = T \sin\theta \; \frac{b\, p_s}{a\, p_w} \left[1 - \frac{\operatorname{Tan}\theta}{\operatorname{Tan}\phi} \right] \qquad \text{(eq.8)}$$

The Return Period of the threshold Rainfall

The return period of the Total of the Catastrophic Rainfall and Average daily rain of catastrophic days is calculated on the basis of the duration of the period 2005 – 2010 following Gumbel, 1954 (Table.6.5) and using the following formula.

$$T = (N+1)/m \qquad \text{(eq.9)}$$

(Gumbel, 1954)

T- Return Period
N-No of years
m- Rank in ascending order

The determination of recurrence interval of the Catastrophic Rainfall

The calculation of recurrence interval of the Total of the Catastrophic Rainfall and Average daily catastrophic rain of days recording more than the calculated threshold rain is done by log probability law following Chow, 1962, 1964 and Schwab et.al. 2002.

$$Xc = x\,(1 + CvK) \qquad \text{(eq.10)}$$

Xc – Calculated Rainfall
x - mean value
Cv – Coefficient of variation
K- Log Probality Frequency Factor (calculated from the table of Chow, 1964)

3.4 Threshold Slope Height to Initiate Slide

Skempton (1953) and Skempton and Hutchinson (1969) in their experience in the development of steep slope and its evolution through slides in the glacial till of County Durham found a critical slope height of 45 m at 30-35^0 steepness. Terzaghi (1962) calculated the critical slope height of the cliff at which failure occurs. In the present study critical height for slope failure is determined after Cullman (1866) and Carson (1977).

$$h_c = -\frac{4c'}{\gamma} \; \frac{\operatorname{Sin}\theta \operatorname{Cos}\phi}{1 - \operatorname{Cos}(\theta - \phi)} \qquad \text{(eq.11)}$$

Where, h_c = Critical (Threshold) Slope Height; c' = Cohesion; ϕ = Angle of Internal Friction; γ =Unit Weight of Materials; θ =Slope Angle.

3.5 Result and Discussion

The investigation with the temporal change in the slide scar reveals that the slope evolution is subjected to a complex interaction between physical and anthropogenic processes. The human action in various developmental activities leads to the development of geomorphic threshold in the form of slope steepness, slope height and threshold rainfall. The estimated geo-technical parameters of the sample collected from the Paglajhora Sinking Zone is summarized in table no.1.

The thickness of the soil and that of the saturated soil during monsoon are measured to be 7.25m at Lower Paglajhora.

The wet soil buck density is measured to be 1.96 g/cc and density of water is 1.07 g/cc applying Keen Box method.

Table1. Calculated geotechnical parameters of two major landslide locations

Sl. No.	Parameters	Lower Paglajhora
1	Major Principal Stress (Kg./sq Cm.)	1.83
2	Minor Principal Stress (Kg./sq Cm.)	0.76
3	Normal Stress (Kg./sq Cm.)	1.10
4	Angle of Rupture (Degree)	35º30′
5	Angle of Internal Friction (Degree)	21º
6	Cohesion (Kg./sq Cm.)	0.06
7	Shear Strength (Kg./sq Cm.)	0.5

3.6 Critical Slope for the initiation of landslideat Paglajhora Sinking Zone

The angle of internal friction varies from 21^0 to 26^0 with an average of 24^0. The spatial distribution of threshold slope depicts that basic requirement for the short term stability of the slope at marginal escarpment slope of Lower Paglajhora to maintain the slope angle of nearer or less than 21^0. A steep slope would decline by slope failure to an angle of repose slope to attain short term stability.

3.7 Threshold Rainfall and landsliding at Paglajhora

The calculated critical rainfall of Tindharia and Lower Paglajhora are 105.88 mm/day and 88.93mm/day respectively (Table.2).

Table2. *Critical rainfall (mm/day) for setting instability* **(***Borga et.al., 1998***).**

Location	**Transmissivity (T)**	Slope(θ)	Contour length (m)	Run-off area sq.m.	Wet soil density	Density of water	Friction angle	Critical Rainfall (mm)
Lower Paglajhora	15 m^{-2} day^{-1}	$48^0 20'$	22.00	968	1.96 g/cc	1.96 g/cc	21^0	**88.928**

A relationship between antecedent cumulative rainfall and landslide vents of 1993, 1998, 2003, 2007 and 2010 was established on the basis of the data recorded from earlier research work done by Ghosh et al. (2009b); Basu et al. (2000) and the collection of rainfall data from nearby Selim Hill Tea Estate by author himself. The 1998 landslide event took place due to 300-600 mm cumulative rainfall in the past 2/3 days only. The two days' antecedent cumulative rainfall was 390 mm was responsible for 1998 landslide events. The major event of 2003 happened due to incessant rainfall of 500 mm in 2 days. 17th and 18th July, 2007 received rainfall of 124.5 mm and 100 mm respectively. These two days' antecedent cumulative rainfall of 224.5 mm caused havoc slope failure at Upper and Lower Paglajhora. Again 2007 faced landslide events on 8th September when 6th, 7th and 8th September's antecedent cumulative rainfall amount was 275 mm. In 2010, major and prominent landslide events happened as a result of 5 days' rainfall of 345 mm at 14 Mile near lower Paglajhora. Antecedent Cumulative rainfall induced landslide analysis shows that the continuous and uniform rate of minimum amount of rainfall (approx. less than 80 mm/day) for few consecutive days can cross the geomorphic threshold and can introduce slope instability condition.

3.8 Average Catastrophic Rainfall since 2005 to 2010 at Paglajhora

The Selim Hill Tea Estate situated 250 m North West of the study area registered 52 days having more than the critical rain fall to initiate threshold condition during last six years between 2005-2010 (Table.3). The determined average rainfall for the 2005, 2006, 2007, 2008, 2009, and 2010, are 120.7 mm., 127 mm., 128.5 mm., 161.12 mm., 141.53 mm and 102.4 mm respectively which are greater than the estimated threshold rainfall from Lower Paglajhora.

Table3. *Analysis of catastrophic rainfall event during 2005 – 2010.*

2005	Rain in mm	2006	Rain in mm	2007	Rain in mm	2008	Rain in mm	2009	Rain in mm	2010	Rain in mm
20th June	95.5	23rd May	103.5	10th June	222.72	7th June	125	3rd June	146.5	24th May	88.9
26th June	**183.5**	28th July	150	28th June	93.5	9th June	100	19th June	133	28th May	101.6
31st July	**134.5**	29th July	160	29th June	120.5	23rd June	203	7th July	175	**16th June**	**111.7**
3rd Oct	100	30th July	112.5	10th July	120	26th June	179	12th July	200.5	14th July	103.6
4th Oct	90	19th Aug	150	**17thJuly**	**124.5**	29th June	196.5	9th Sep	98.7	18th July	102
		31st Aug	120.5	**18th July**	**100**	7th July	273.5	27th Sep	95.5	25th July	92.4
		17th Sep.	89.5	27thJuly	120.5	8th July	162.5			5th Aug	114.3
		3rd Oct	130	18th Aug	145.5	21st July	146.5			25th Aug	89.4
				23rd Sep.	106.2	28th July	148.5			28th Aug	102.6
						30th July	100			16thSep.	115.5
						10th Aug	191.5			25thSep.	116.3
						31st Aug	107.5			26thSep.	90.5
No of Days	**5**		**8**		**9**		**12**		**6**		**12**
Total	**603.5**		**1016**		**1153.42**		**1933.5**		**849.2**		**1228.8**
Average	**120.7**		**127**		**128.15**		**161.12**		**141.53**		**102.4**

Source: *Selim Hill Tea Estate (1/2 km. Crow fly dist. from the studied locations).*

4. Return period of Rainfall at Paglajhora

The total catastrophic rain of more than the calculated threshold value of the year 2005 has a return period of 7 years and the average catastrophic daily rain of more than the calculated threshold rain that received in 2005 can be experienced with a recurrence interval of 7 years (Table.4).

Table.4:Return Period of Catastrophic Rainfalls after Gumbel, 1954.

Year	No of Days of Catastrophic Rainfall	Total of the Catastrophic Rainfall	Arranged in descending order	Rank	T= (N+ 1)/m (Gumbel , 1954)	Average daily rain	Arranged in descending order	Rank	T= (N+ 1)/m (Gumbel ,1954)
2005	5	603.5	1933.5	1	7	120.7	161.12	1	7
2006	8	1016	1228.8	2	3.5	127	141.53	2	3.5
2007	9	1153.42	1153.42	3	2.33	128.15	128.15	3	2.33
2008	12	1933.5	1016	4	1.75	161.12	127	4	1.75
2009	6	849.2	849.2	5	1.4	141.53	120.7	5	1.4
2010	12	1228.8	603.5	6	1.16	102.4	102.4	6	1.16
Mean			1130.7367			130.1500			
Std Deviation			452.7617			19.8087			
Coefficient of Variation			0.4000415			0.152199			

5. PROBABILISTIC RECURRENCE INTERVAL OF RAINFALL

The daily average catastrophic rain (more than the calculated threshold) that can be experienced at a recurrence interval of 20 years (with 5% probability) is 164.97 and that at a recurrence interval of 5 years (with 20% probability) is 131.793 (Table.5).

Table.5: Amount of Rain fall at Certain Probability and with specific return period (After Chow, 1951 and 1954).

P %	T (Years)	K	Xc (mm)
99	**1.01**	**-2.001**	**90.539**
50	**2**	**-0.083**	**128.507**
20	**5**	**0.083**	**131.793**
5	**20**	**1.759**	**164.971**
1	**100**	**2.669**	**182.985**

The calculation shows that 88.928mm daily rainfall is the threshold rain for Paglajhora and the analysis of return period shows that 120.7 mm daily rainfall can occur at a recurrence interval of 1.4 years following Gumbel, 1954 and 128.507 mm daily rain has a recurrence interval of 2 years with 50% probability following Chow, 1951 and 1954. That means there is every possibility for the generation of geomorphic threshold for initiation of slide due to hydrologic factor. At Paglajhora the critical rainfall is 88.93mm which is less than the estimated rainfall of 90.54 mm at the recurrence interval of 1.01 year with 99% probability. So it can be inferred that Paglajhora is a place of higher probability of rainfall triggering landslide phenomena in every rainy season.

6. Calculated Critical Height in landsliding at Paglajhora

The determined critical slope height after Cullman, 1866 and Carson, 1971 of the places Lower Paglajhora is 7.80 m. The height of the vertical back wall along the road should be restricted to almost 6.00 m. in Paglajhora. The landslide affected area in Darjiling Himalaya with more than 6.00 m height corresponding to the average threshold slope angle of 21^0 to 24^0 must be identified and shaped to that of safe height (below 6.00 m.). It is observed that the physical and anthropogenic processes are active on slope in an interactive combination. Construction of road and associated deforestation destabilize soil and slope. Slope is steepened, soil becomes loose and friable, lateral support is removed, soil becomes saturated by hydrological intervention. All these together leads to instability and threshold condition are achieved. Ultimately slope failure occurs and that helps to achieve temporary stability in the mountain terrain.

Table9. *Critical Height for initiation of slide at two major landslide locations.*

Sl. No.	Slope Parameters	Lower Paglajhora
1	Upslope Contributing area (a)	968 m^2
2	Contour length (b)	22m
3	Slope angle (Θ)	$48^0 20^/$
4	Angle of Internal Friction (φ)	21^0
5	Transmissivity (T)	15 m^{-2} day $^{-1}$ (Borga et.al 1998).
6	Wet soil buck density (P_s)	1.96 g/cc.
7	Density of water(P_W)	1.07 g/cc
8	Cohesion (Kg. /sq Cm.)	0.06
9	Critical Height for Initiation of Slide Cullman,1866 and Carson,1971 $h_c = \frac{4c^/}{\gamma} \cdot \frac{\sin\theta \cos\phi}{1 - \cos(\theta - \phi)}$	7.80m

7. CONCLUSION

Slope map of the watershed reveals that it varies from very gentle gradient (around 10º*)* in the mid central & mid-lower part to that of high (more than 60º), towards the marginal part/water divide. The major landslide locations are registered with the slope angle ranges between 40^0 and 60^0. The study depicts the positive relationship between the slope steepness and the occurrences of landslide phenomena in the Paglajhora area. Analysis states that more than 60% area of the Sinking zone experiences above average threshold slope angle of 24^0. The lineaments at the places of Lower Paglajhora are closely spaced. The study depicts that the all the physiographic parameters of the soil changes the geomorphic threshold and initiate slope instability. In Paglajhora area, the physiographic configuration along with fragile lithology, drainage concentration, and moderate to steep slopes create favourable environment for landslips. Not only that the area is intersected by number of first order streams which helps seepage and slope materials saturation and consequently reduces cohesion and shear strength of slope materials and finally promote slope failure.

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