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Thresholds for the Evolution of Mining Scars on Himalayan Slope at Darjiling, West Bengal

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Abstract: *Identification of the processes involved in slope failure and understanding their interaction is important for better management of mining scars along the southern escarpment slopes of the Himalaya. The mining and associated anthropogenic processes make the slope steeper than their repose angle varying from 19° to 23°, introducing instability into the system. Considering the pore water pressure, the threshold angle reduces to 9°51′. Measurements taken at the back wall of the mining scars reveal that the thicknesses of the total soil are 4.5 m in mining pit 1 and 7.25 m in mining pit 2. The thickness of saturated soil in mining pit 1 and mining pit 2 are 1.28 m and 1.30 m respectively. The excavation makes the slope steeper and longer, removes the lateral and basal support, disturbs the soil, favours infiltration and throughflow, and helps in the increase of wet soil depth. All these changes and their combined effects alter the geomorphic threshold of the system. The calculation shows that 94.05 mm and 39.53 mm daily rainfall are critical for initiation of slide on mining pit-1 and 2 respectively. Following Log Probability Law it has been calculated that 128.507 mm daily rain is expected in this region at a recurrence interval of 2 years with 50% probability. The critical slope height becomes 5.89 – 9.30 m for mining pit 1 and 7.80 – 9.30 m for pit 2. As the slope angle and height on the scar face exceeds the critical values, debris slide occurs during rain and the slope on scar face is reduced to that of the angle of repose and the slope attains temporary stability through internal feedback in a process of homeostatic adjustment.*

Introduction

The evolution of hill slope is a complex phenomenon influenced by the systematic interaction between sets of physical and manmade factors governed by geologic, hydrologic, climatic, geomorphic and landuse attributes. The seasonal mining from slopes by excavation as well as by rat-hole drilling during dry winter and subsequent action of rainwater on those mining scars and debris during monsoon through sliding and washing, set up a rhythmic process of de-stabilisation, threshold generation and ultimate debris slide for attaining new equilibrium. The seasonal debris slide on the temporarily settled but dislodged material is studied intensively for the cognition of the processes interacting together leading to the development of geomorphic, hydrologic and geotechnical thresholds. Slope failure is visualised as an episodic event which occur as a result of exceeding the threshold, that may be either intrinsic, gradual and cumulative change in the internal structure or extrinsic, imposed from outside by either hydrologic or anthropogenic factors. Assessment of the geomorphic attributes like critical slope is of utmost importance as an essential factor of instability in association with co-efficient of friction, angle of repose, weight of soil and slope angle on scar face (Jumikis, 1967; Melnikov, *et al.*, 1969); porewater pressure on potential sliding surface, depth of potential shear plane, and bulk unit weight of the sliding materials (Carson, 1975); thickness of total soil, thickness of saturated soil, wet soil density, density of water, angle of repose and slope angle on scar face (Borga *et al.*, 1998). The threshold slope height is estimated following Cullman (1866), Carson (1971) and Terzaghi (1962). The hydrologic factors like daily rainfall threshold in connection to slope angle and regolith thickness (Gabet *et al.*, 2004), rainfall intensity, infiltration, transmissibility, average slope on steep back wall, slope curvature, wet soil density, density of water and angle of internal friction (Borga et al., 1998) are considered as a contributor of slope instability. Montgomery and Deitrich (1994); Deitrich and Montgomery (1998); Fernandes *et al.*, (2004) introduced another set of variables like cohesion, gravitational acceleration, etc. for an improved calculation of threshold rainfall for initiation of slide. The cognition of probable interaction among the major factors helps in the assessment of processes and in their management for the restoration of slope to ensure optimum utilisation of land and mineral resources (Ahnert, 1977; Kirkby, 1980; Poesen, 1985 and Ploey, 1982).

The study area

The stability of the slope has been greatly disturbed at Tindharia located within 26°50′10″N to 26°50′40″N and 88°19′50″E to 88°20′00″E, in Darjiling District of West Bengal due to the mining of coal from the hill slope through crude and traditional methods by removal of slope cover, excavation to remove overburden, tunnelling or rat-hole drilling, back cutting etc. The slope in this section is lithologically and tectonically unstable being composed mainly of slightly altered, crushed and friable quartzite and carbonaceous sandstone, shale, slate, siltstone and micaceous quartzite along with remarkable presence of coal seams. The presence of coal seams reduces the cohesion of soil and debris. The crushed and friable nature of coal is due to the intensive thrusting as these formations are sandwiched between two thrusts — viz. Main Boundary Thrust to the south and Dalling Thrust to the north (Fig. 1). The thrusting effects are pronounced on Damuda Shales intercalated with semi-anthracitic coal seams. Furthermore, the rat-holes and tunnels are drilled on the temporarily settled upslope materials which were dislodged in previous slide during 1968 (Basu and Ghatowar, 1988). Thus due to the removal of basal, lateral and underlying support the slope becomes extremely unstable. The tunnelling and back cutting on temporarily settled debris develop steep secondary slope on the margin of mining pits, contributing to the generation of conditions which invite debris slide in saturation condition during every monsoon. The heavy rainfall (more than 460 mm per year) results in deep seated chemical weathering and the development of expansion cracks lead ultimately to block disintegration and landslide. After the slide, the steepness of secondary slope on pit margin or pit head reduces so that the angle of repose gets temporary stability. After the monsoon, in November the locals either start reopening the pits by removing the debris cover, or climb upslope for excavation of fresh pit. More and more slope area thus comes under this destructive action and the

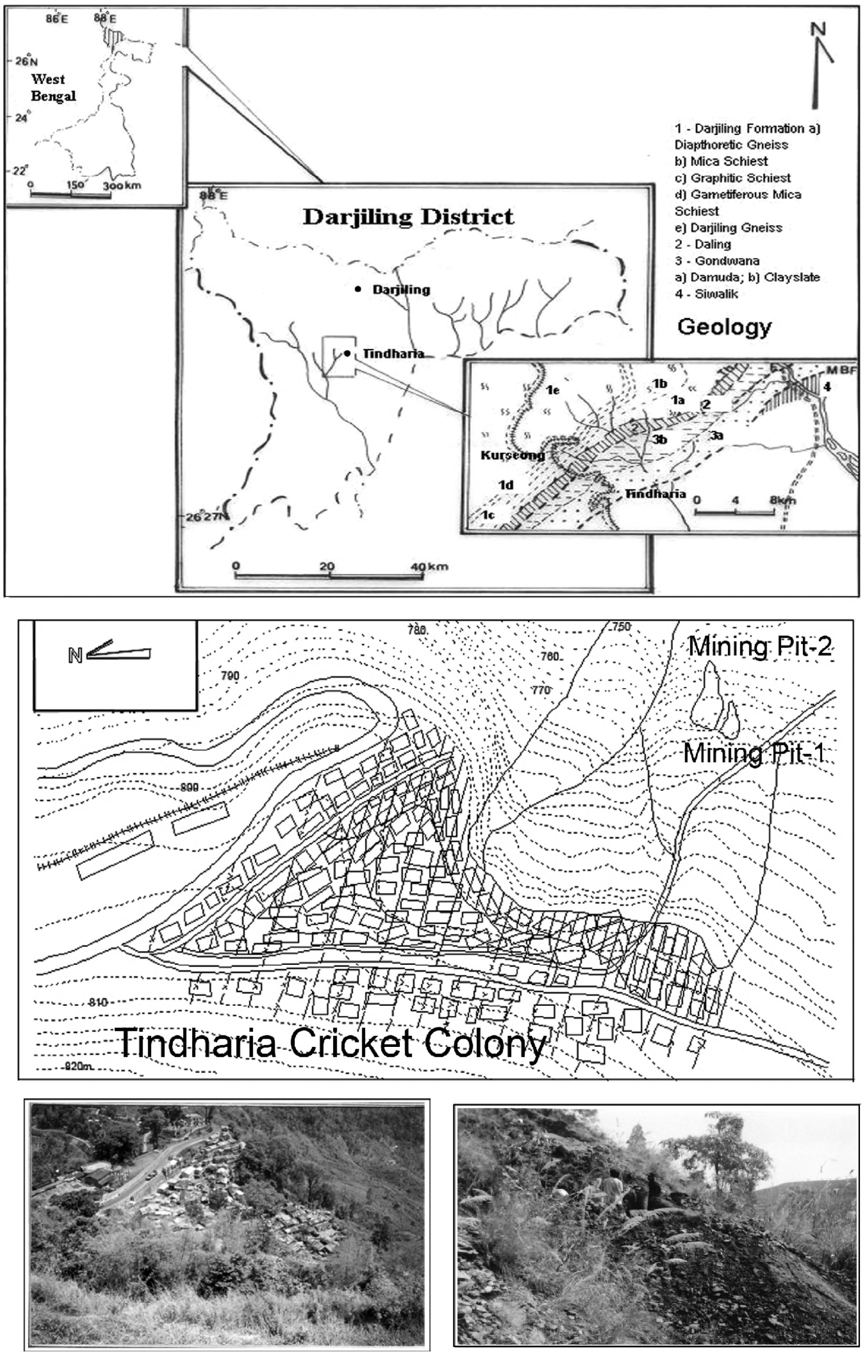

Figure 1. The location and geology of the study area

whole region is subsiding at a faster rate. The subsidence is being manifested by the tilting and development of cracks on the floor and wall of the houses at Tindharia Cricket Colony village lying immediately upslope of the affected area.

Materials and Methods

In order to investigate into the evolution of mining-induced slope through cognition of the systematic association of the processes leading to the development of geomorphic thresholds, repeated field surveys were conducted. The processes acting on the concerned slope come under two broad groups - the anthropogenic processes and natural processes. The anthropogenic processes include slope clearing, excavation, back cutting, rat-hole drilling, extraction of resource and down slope disposal of debris and over burden material. The natural processes include, sliding and down slope washing of debris during monsoon in saturated condition and is regulated again by two sets of factors i.e. topographic and hydrologic. The topographic factors mainly consider slope steepness, slope length, contributing area and concavity of the slope. These parameters are measured in field in consultation with Survey of India Topographical map (78B/5, on 1:50,000). Slope length and upslope contributing area are measured by locating the divide on the topographical map and measuring distance from it. The concavity is measured by the ratio between area (a) and contour length (b). The measurement of width, depth, area and gradient of the mining scar is done by field techniques with appropriate accessories. The depth of the slide scar is measured by holding a measuring tape at both the margins of scar and the other tape is allowed to hang. The reading is then taken from the base of the hanging tape. Margins of the scars are surveyed by prismatic compass and total station. The intensive survey of the mining-cum-sliding scar is carried on by Abney's level at 0.5 m interval along radial lines originating from lower most part of the scar. The altitudes of the points at 0.5 m interval along the radial lines are then estimated in reference to the central base point of known altitude determined by GPS. Repetitions of such surveys help to generate a series of maps which could be used for change detection in length, width and area of a particular scar. An attempt is also made to investigate into the processes involved in the evolution of the concerned scar. The rainfall data is collected from Selim Hill Tea Estate situated within 250 m distance. Pore water pressure is calculated after Carson (1975). The critical slope angle for the initiation of slide is estimated after Jumikis (1967), Melnikov *et al.* (1969), Borga *et al.* (1998) and Carson (1975). The critical height of steep slope is calculated after Cullman (1866), Carson (1971) and Terzaghi (1962). The total thickness of soil and that of saturated soil during monsoon is measured from slope cutting. The rain is the most important factor for triggering slide by introducing lubrication and increasing the weight of soil in saturation condition. Thus it is possible to determine the critical rainfall (r_{cr}) which can cause instability after Borga *et al.*, (1998). The geo-technical factor like angle of repose of the debris is measured by the method proposed by Bloom (1991) and Pethick (1984). The tangent of angle of repose of dry granular materials is taken to be approximately equal to the co-efficient of sliding friction of the material or its mass friction (f) (Van Burkalow, 1945 and Bloom, 1991). The cohesion and angle of internal friction is measured by tri-axial compression test following Mohr stress Diagram in the geotechnical laboratory of Geological Society of India (GSI).

Results: Evolution of the mining pits

Mining and associated excavation, back-cutting and removal of unconsolidated over burden from steep mountain slope essentially develop a scar on the slope surface (Fig. 2). The slope on the back wall of the scar becomes steeper and longer during mining season by further back cutting and excavation (Fig. 3). Thus the geomorphic threshold is attained which ultimately leads to absolute instability in saturated condition during next monsoon. The depth of the scar decreases during rain by partial filling of depressions with up-slope materials supplied by sliding and slope washing

Table 1. The Geomorphic attributes of mining pits 1 &2 and their evolution since Feb-2000

	Max. Length (m)	Max. Width (m)	Max. Depth (m)	Avg. Depth (m)	Affected Area (m^2)	Steepness of Back wall (deg)	Height of Back wall (m)	Thickness of the total soil (m)	Thickness of the saturated soil (m)	Remark
Mining Pit-1										
Feb 2000	12.75	10	5.75	1.25	72	60	4	4.5	-	
Oct 2000	15	12	3.75	0.75	79.92	20	1.25	4.5	1.2	Reduction of steepness, height of back wall by sliding
April 2001	21.5	21	5	0.5	184.5	45	4.5	4.5	-	
June 2004	24	21.6	3	1	300.37	22	0.75	4.5	-	
Sep 2004	32	22.5	3.5	0.75	378	55	5.5	4.5	1.36	
Oct 2005	33.5	25	3	0.5	398	21	1.28	4.5	1.3	Reduction of steepness, height of back wall by sliding
Jan 2006	34.5	27	4	0.5	401	21	2	4.5	-	
Mining Pit-2										
Feb 2000	16	12.2	6	3.75	96.48	50	6	7.25		
Oct 2000	20.15	15.75	4.6	3.00	162.5	31	1.5	7.25	1.25	Reduction of steepness, height of back wall by sliding
April 2001	22.30	18.25	3.5	2.25	216	45	7.25	7.25	-	
June 2004	28.40	19.7	2.3	1.65	350	25	4	7.25	-	
Sep 2004	32	22	4	2.50	400	50	6.30	7.25	1.35	
Oct 2005	-	-	-	-	-	-	-	-	-	
Jan 2006	-	-	-	-	-	-	-	-	-	

(Fig. 4) (Basu and Maiti, 2001). Debris slide on the mining scar occurs when the threshold value is exceeded and thus the steepness and length of the slope are reduced to attain temporary stability. The result of the study during February, 2000 to January, 2006 on mining pit 1 and 2 is tabulated (Table 1). The temporal change in size and shape of the mining scars is represented by superimposing the maps of different periods in Fig. 4a and 4b. Both natural and anthropogenic processes are active in an interactive combination resulting in sliding that contribute to the spatial increment of mining scars which gradually spread upward bringing more and more area under this destructive operation.

Measurements taken at the back wall of the mining scars reveal that the thicknesses of the total soil are 4.5m in mining pit 1 and 7.25m in mining pit 2. The thickness of saturated soil in mining pit 2 and mining pit 2 are 1.28 m and 1.30 m respectively. The value of wet soil bulk density is found to be 1.96 g cc^{-1} and density of water is 1.07 g cc^{-1}. The angle of internal friction varies from 19° to 23° with an average of angle 21°. The

Table 2. Geotechnical attributes of slope forming materials at mining pits

Major Principal Stress (kg cm^{-2})	1.83
Minor Principal Stress (kg cm^{-2})	0.76
Normal Stress (kg cm^{-2})	1.10
Angle of Rupture (degree)	56
Angle of Internal Friction (degree)	21
Cohesion (kg cm^{-2})	0.06
Shear Strength (kg cm^{-2})	0.50

saturated conductivity of the soil varies from 10^{-2} m s^{-1} for the soil depth less than 0.5 m to 10^{-5} m s^{-1} for soil depth between 1 to 2 m (Fenti, 1992; Freeze and Cherry, 1979 and Bedinent *et al.*, 2008). Based on these and other data, Matteotti (1996) estimated the transmissivity (T) of saturated soil to vary between 5 and 30 m day $^{-1}$, with a mean value of 15 m day $^{-1}$ (Borga *et al.* 1998). For a soil depth of 5 m the variation of saturated hydraulic conductivity is estimated to be between 1.0×10^{-6} to 9.0×10^{-5} m s^{-1} measured by Permeameter. The field observation on the near vertical mining scar face during heavy rain shows an average of 12 cm h^{-1} vertical penetration of water with a considerable variation in different soil horizons. Considering this observed rate, the estimated Transmissibility value becomes 12.96 and 20.80 m day^{-1} for pit 1 and pit 2 respectively. This corresponds to Fenti (1992); Freeze and Cherry (1979); Matteotti (1996); and Bedinent *et al.* (2008). Result of the geotechnical analysis shows that the constituent materials are mainly cohesionless partially consolidated debris.

Discussion

The investigation on the temporal change in the slide scar reveals that slope evolution here is subjected to a complex interaction between physical and anthropogenic processes. Human action of mining through back cutting leads to the development of geomorphic threshold in the form of slope steepness and slope height which causes slope failure in saturation condition during monsoon. Thus it is important to estimate the threshold condition in terms of steepness, slope height and critical rainfall.

Estimation of thresholds for initiation of slide

THRESHOLD SLOPE ANGLE

The steepening of slope at the back wall of the mining scar by back cutting, excavation and tunnelling is mainly responsible for instability, as the slope on the marginal escarpment of scar becomes greater than the angle of repose.

The stability equation (Equation 1; Table-3) for a mass of loose, friable and cohesionless debris after Jumikis (1967) and, Melnikov *et al.* (1969) describes that angle of repose must be greater or equal to the slope on scar face for attaining unconditional stability. Carson (1975) introduced pore water pressure to estimate critical angle of slope failure (Equation 2; Table-3). Pore water pressure is calculated by Jumikis (1967) and Terzaghi (1962) (Equation 3; Table 3). The hydraulic head (dh) is measured in field during rainfall from the boreholes and horizontal distance between two boreholes (dl) is measured with measuring tape.

The other slope stability model (Equation 4; Table 3) for cohesionless material and slope parallel seepage after Borga *et al.* (1998) also

Table 3. The critical slope angle to initiate debris slide

Methods	Jumikis (1967), Melnikov, Chesnokov Fienbarg *et al.* (1969)	Carson (1975)	Borga *et al.* (1998)
Formulae	$(W\mathrm{Cos}\theta\ \mathrm{Tan}\phi)$ / $W\mathrm{Sin}\theta > 1$. ....(1) or, $\phi \geq \theta$ (Dry Condition) $\mathrm{Tan}\phi$ = Co-efficient of friction ϕ = Angle of repose W = Weight of soil θ = Slope on scar face	$\mathrm{Tan}\,\alpha =$ $(1-u / \gamma z\, \mathrm{Cos}^2 \alpha)\, \mathrm{Tan}\phi$ ....(2) (Introducing pore water pressure in saturated condition) α = Threshold angle of failure u = Pore water pressure on potential sliding surface z = depth of potential shear plane γ = Bulk unit weight of the sliding materials ϕ = Angle of repose $u = rw\, dh/dl$ ....(3) Jumikis (1967) and Terzaghi (1936) u = seepage pressure, rw = unit weight of water, dh/dl = hydraulic gradient.	$\frac{h}{z} = \frac{Ps}{Pw}\left(1 - \frac{Tan\theta}{Tan\,\phi}\right) > 1$ ....(4) (Dry Condition) h = Thickness of total soil z = Thickness of saturated soil Ps = Wet soil density Pw = Density of water ϕ = Angle of repose θ = Slope on scar face.
Threshold Slope Angle	$\theta = 21° - 26°$	$\alpha = 9°51'$	$\theta = 21° - 26°$

supports the view of Jumikis (1967) and Melnikov *et al.* (1969). All the stability equations consider angle of internal friction as the most important factor of instability that depends on the material quality and amount of moisture. The resistance to movement is guided mainly by coefficient of internal friction. The resistance declines as the moisture content of the material increases and seepage pressure increases. The average steepness of marginal scarp slopes of the mining pits 1 and 2 are 53° 20′ and 48°20′ respectively, which exceeds the angle of repose. In the present study the angle of repose in sun-dry condition for the concerned material varies from 21° to 26°. The basic requirement for the short term stability of the slope at marginal scarp of mining pits is to maintain the steepness near or less than 21° (Table 3). But in maximum cases, during mining season the scarp slope becomes twice or sometimes thrice to that required for stability and thus geomorphic threshold is crossed and the steep slope declines by slope failure to an angle of repose to attain short term stability (Wallace, 1977).

THRESHOLD SLOPE HEIGHT

Cullman (1866) and Carson (1971) attempted the calculation of critical slope height by equating material cohesion (c′), angle of internal friction (ϕ) and unit weight of materials (W) with slope steepness (θ) (Equation 5; Table 4). The critical heights for initiation of slide are 5.89 m and 7.80 m respectively (Table

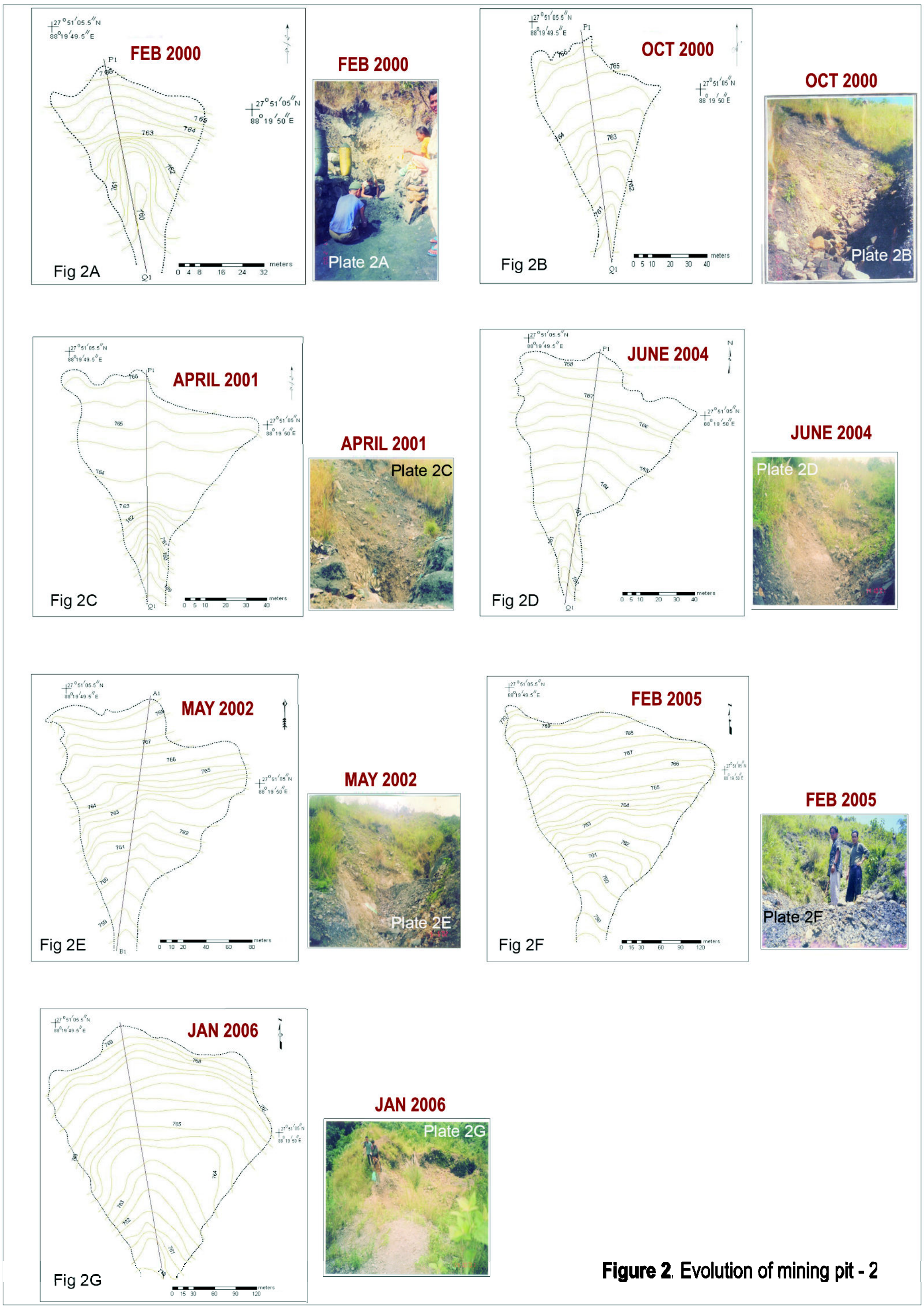

Figure 2. Evolution of mining pit - 2

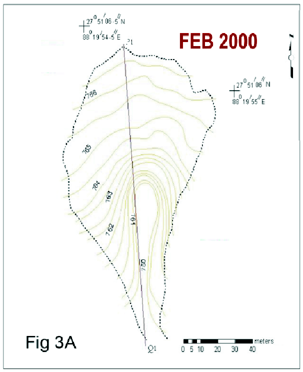

Fig 3A

FEB 2000

Plate 3A

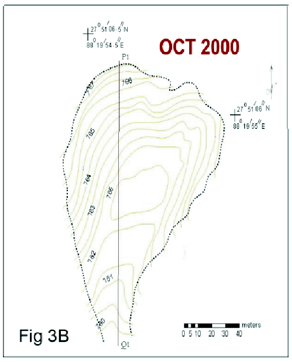

Fig 3B

OCT 2000

Plate 3B

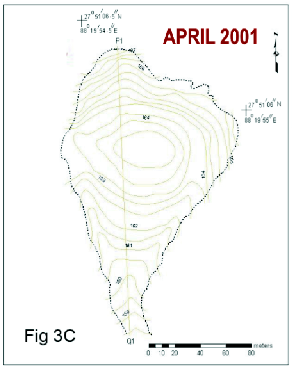

Fig 3C

APRIL 2001

Plate 3C

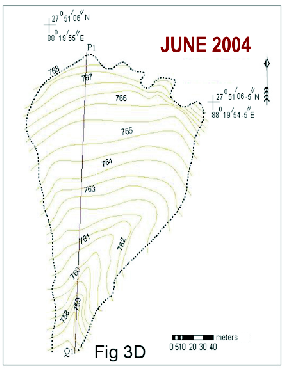

Fig 3D

JUNE 2004

Plate 3D

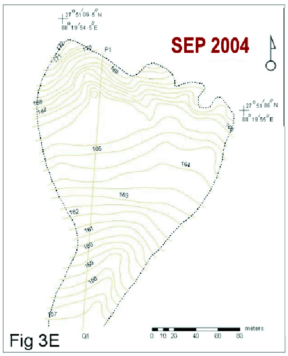

Fig 3E

SEP 2004

Plate 3E

Figure 3. Evolution of mining pit - 1

Table 4. The threshold slope height to initiate debris slide

Slope Parameters	Mining Pit - 1	Mining Pit - 2
Slope on scar face (θ) (Mining Period)	53°20′	48° 20′
Angle of internal friction (ϕ)	21°	21°
Wet soil buck density (P_s)	1.96 g cc^{-1}	1.96 g cc^{-1}
Density of water (P_W)	1.07 g cc^{-1}	1.07 g cc^{-1}
Cohesion (c′ in kg cc^{-2})	0.06	0.06
Critical height for initiation of slide (h_c) Cullman,1866 and Carson,1971 $h_c = \frac{4c'}{\gamma}\left(\frac{\sin\theta\cos\phi}{1-\cos(\theta-\phi)}\right)$ ....(5) γ= Bulk unit weight of sliding material	5.89 m	7.80 m
Critical height for initiation of slide (*Hc*) Terzaghi (1962) $H_c = \frac{Sc}{W}$ ....……………… (6) Sc = Compressive strength of the rocks W = Unit weight of the rocks	9.30 m	9.30 m

4) for mining pits 1 and 2. Terzaghi (1962) defined critical slope height as a ratio between compressive strength of the rocks (Sc) and unit weight of the rocks (W) (Equation 6, Table 4) and, based on this, the value for the study area comes to 9.30 m (Table 4). 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 Durham county found a critical slope height of 45 m at 30°–35° steepness. At Tindharia, it is found that in saturated condition, unconsolidated materials collapse before attaining the critical height.

THRESHOLD RAINFALL

In absolutely instable condition, it is essential to estimate the critical rain to initiate slide. Borga *et al.* (1998) introduced a model (Equation 6, Table 5) for assessing threshold rain on unconsolidated materials in association with transmissibility, average slope on steep back wall, surface curvature, wet soil density, density of water and angle of internal friction. The rainfall of –91.41 mm day^{-1} and –124.56 mm day^{-1} are estimated to be critical for initiation of slide on mining pits 1 and 2 (Table 5). As the slope on scar face exceeds the angle of friction, absolute instability develops which is indicated by the negative value of the critical rain. The value becomes positive if the slope becomes equal or less than the angle of internal friction. To avoid this negative value for the slopes greater than angle of internal friction, Montgomery *et al.* (1998) and Fernandes *et al.* (2004) introduced a formula for estimating threshold rain and, according to it, the values become 94.05 mm and 39.53 mm respectively for mining pits 1 and 2. The variation of critical rain from mining pit 1 to that of mining pit 2 is due to the difference in the surface curvature.

A weather station at Selim Hill Tea Estate situated 250 m northwest of the study area, recorded that between 2000 and 2006, 52 days received more than the critical rainfall required to initiate landslides (Table 6).

The calculation of recurrence interval of the catastrophic rains (those above the calculated threshold) is done by log probability law following Chow (1954) and Schwab *et al.* (2002).

$Xc = x\ (1 + C_v K)$..................... (7)

Xc: Calculated daily rainfall

x: Mean value of daily rainfall

C_v: Coefficient of variation

K: Log Probability Frequency Factor

Table 5. The critical rainfall to initiate debris slide

	Mining Pit 1	Mining Pit-2
(T) = Transmissibility	12.96 m^2 day^{-1}	20.80 m^2 day^{-1}
(θ) = Average slope on steep back wall	53°20′	48°20′
(b) = Contour length (m)	27	22
(a) = Runoff contributing area (m^2)	1404	968
(p_s) = Wet soil density	1.96 g cc^{-1}	1.96 g cc^{-1}
(p_w) = Density of water	1.07 g cc^{-1}	1.07 g cc^{-1}
(ϕ) = Angle of internal friction	21°	21°
Critical rainfall for setting instability (r_{cr} in mm day^{-1}) (Borga *et al.*, 1998) $r_{cr} = T\frac{b}{a}\sin\theta\frac{Ps}{Pw}\left(1-\frac{Tan\theta}{Tan\phi}\right)$……………………………….(6)	–91.41	–124.56
Critical rainfall for setting instability (Q_c in mm/day) (Montgomery and Deitrich, 1994; Deitrich and Montgomery, 1998; Fernandes et al., 2004) $\frac{Q_C}{T} = \frac{b}{a}\sin\theta[\ \frac{C'}{\rho_W gz\cos^2\theta\tan\phi} + \frac{Ps}{Pw}\left(1-\frac{Tan\theta}{Tan\phi}\right)$………..(7)	94.05	39.53

Table 6. Storm rainfall between 2000 and 2006

2000	Rainfall (mm)	2001	Rainfall (mm)	2002	Rainfall (mm)	2003	Rainfall (mm)	2004	Rainfall (mm)	2006	Rainfall (mm)
20 June	95.5	23 May	103.5	10 June	222.7	7 June	125.0	3 June	146.5	24 May	88.9
26 June	183.5	28 July	150.0	28 June	93.5	9 June	100.0	19 June	133.0	28 May	101.6
31 July	134.5	29 July	160.0	29 June	120.5	23 June	203.0	7 July	175.0	27 June	111.7
3 Oct	100.0	30 July	112.5	20 July	120.0	26 June	179.0	12 July	200.5	14 July	103.6
4 Oct	90.0	19 Aug	150.0	21 July	124.5	29 June	196.5	9 Sep	98.7	18 July	102.0
		31 Aug	120.5	23 July	100.0	7 July	273.5	27 Sep	95.5	25 July	92.4
		17 Sep.	89.5	27 July	120.5	8 July	162.5			5 Aug	114.3
		3 Oct	130.0	18 Aug	145.5	21 July	146.5			25 Aug	89.4
				23 Sep.	106.2	28 July	148.5			28 Aug	102.6
						30 July	100.0			16 Sep.	115.5
						10 Aug	191.5			25 Sep.	116.3
						31 Aug	107.5			26 Sep.	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

(Calculated after Chow, 1954)

The calculation shows that 91.41 mm day^{-1} and 124.56 mm day^{-1} rainfall are the threshold rain for mining pits 1 and 2 respectively and the analysis of return period shows that 128.51 mm daily rain has a recurrence interval of 2 years with 50% probability following Chow (1954). That means there is a high possibility for the rainfall to cross the geomorphic threshold for initiation of slide in every alternate year.

Conclusion

Anthropogenic actions make the slope steeper, destabilise the materials and increase the concavity of surface by removal of overburden

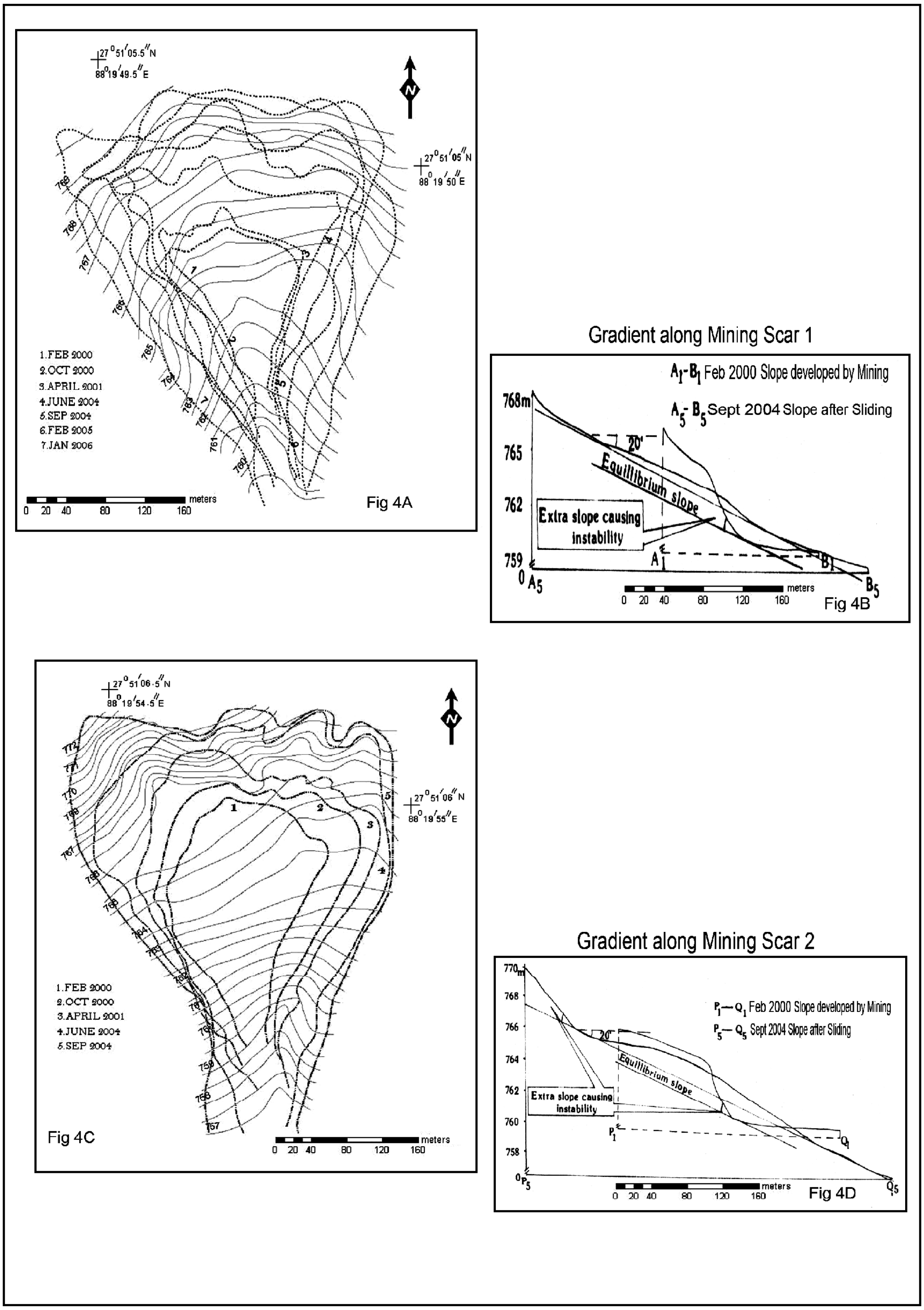

Figure. 4. Superimposed mining scars in plan and profile

Table 7. Amount of rain fall at certain probability and with specific return period (After Chow, 1954)

P %	Years	Log Probability Frequency Factor (K)	Calculated daily rainfall in mm (Xc)
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

and favours infiltration through dissected slope. This infiltration increases the depth of saturated soil. Density of wet soils becomes an important factor of instability, although porewater pressure or seepage pressure is negligible due to immediate drainage through porous medium. The rainfall character of the study area shows the possibility of crossing the threshold rainfall in every alternate year. The primary condition of stability is to maintain the steepness of scar face and margin at or below the angle of repose. The most important triggering factor thus seems to be the steepness of back wall that are more than twice of the threshold gradient. The study shows that the back wall collapses before attaining critical slope height due to its excessive steepness. The estimated critical rain also becomes negative as the slope far exceeds the repose angle that leads to absolute instability. The natural processes respond to such change in slope, soil and water and try to bring equilibrium by reducing the height and steepness of the slope along the scar margin by self-organised adjustments. After every debris slide the slope on the scar face attains steepness ranging from 20° to 24° that is close to that of repose angle. Thus, in the study area the slope undergoes a seasonal rhythm of instability through mining and subsequent homeostatic adjustment through sliding. It is concluded that the back wall of mining scars at Tindharia cannot be allowed to cross 21° steepness and

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mining and degradation of slopes in the Darjeeling Himalayas, In Basu, S.R. (ed), *Proceeding: International Seminar on Changing Environmental Scenario of the Indian Subcontinent*, 390–399.

Bedinent, P.B, Huber, W.C. and Vieux, B.E. (2008) *Hydrology and Floodplain Analysis*, 4th Ed. Prentice-Hall Publishing Co., Upper Saddle River, NJ: 795p.

Bloom, A.L. (1991). *Geomorphology: A systematic analysis of late Cenozoic Landforms*. Prentice Hall of India Pvt. Ltd., New Delhi: 76–177.

Borga, M., Fontana, D.G, Ros, D.D. and Marchi, L. (1998) Shallow landslide hazard assessment using physically based model and digital elevation data. *Environmental Geology*, 35(2-3): 81–88.

Carson, M.A. (1971) Application of the concept of threshold slopes to the Laramie Mountains, Wyoming, *Institute of British Geographers, Special Publication*, 3: 31–48.

Carson, M. A. (1975) Threshold and characteristic angles of straight slopes, *Proceedings of the 4th Guelph Symposium on Geomorphology*, Norwich Geo Books, 19–34.

Chow, V.T. (1954) The log probability law and its engineering applications, *Journal of Hydraulics Division, ASCE*, 80 (Separate 536): 25p.

Cullman, C. (1866) *Die graphische Statik*, Zurich, Verlag van Meyer and Zeller.

Dietrich, W.E. and Montgomery, D.R. (1998). *SHALSTAB: A digital terrain model for mapping shallow landslide potential*. National Council of the Paper Industry for Air and Stream Improvement (NCSAI), Technical Report: 29p.

Fenti, V. (1992) Indagini geologico-tecniche sull'area del dispositivo di misura (in Italian) in

Marchi, L. (ed) II *Basino attrezzato del Rio Cordon, Quaderni di Ricerca*, n. 13, Regione Veneto. Dipartimento Foreste, Venezia Mestre: 109–122.

Fernandes, N F., Guimaraes, R.F., Gomes, R.A.T., Vieira, B.C., Montgomery, D.R. and Greengerg, H. (2004) Topographic Controls of landslides in Rio de Janerio: field evidences and modelling, *Catena*, 55: 163–181.

Freeze, R.A. and Cherry, J.A. (1979) *Ground Water*, Englewood Cliff, N.J: Prentice Hall: 604p.

Gabet, J.E; Burbank, W.D; Putkonen, K.J; Pratt-Sitaula, A.B.; Ojha, T. (2004) Rainfall threshold for land sliding in the Himalayas of Nepal, *Geomorphology*, 63(1-4):131–143.

Jumikis, A.R. (1967) *Soil Mechanics*, Prinston, New Jersey, D. Nostrand Company, Inc.: 436p.

Kirkby, M.J. (1980) Modelling water erosion processes In, Kirkby, M.J.and Morgan, R.P.C. (eds.) *Soil Erosion,* New York: John Wiley and Sons: 183–216.

Matteotti, G. (1996) *Valutazione del rischio di franosita per unbacino di tipo alpino*, Ph.D. Dissertation, University of Padova, Italy.

Melnikov, M. and Chesnokov, M. and Fienberg, H. (1969) *Safety in Opencast Mining*, Moscow: Mir Publications: 391p.

Montgomery, D.R. and Dietrich, W.E. (1994) A physically based model for the topographic control on shallow land sliding, *Water Resources*, 30: 1153–1171.

Montgomery, D.R. Sullivan, K. Greenberg, M.H. (1998) Regional test of a model for shallow landslide, *Hydrological Processes*, 12: 943–955.

Pethick, J. (1984). *An Introduction to costal Geomorphology*, Edward Arnold Publication. London: 73–74.

Ploey De. J. (1982) A stemflow equation for grasses and similar vegetation, *Catena*, (9): 39–52.

Ploey. D.J. and Poesen, J.(1987) Geomorphological models – Theoretical and Empirical Aspects, *Catena Supplement* (10): 67–72.

Poesen, J.(1985) An improved splash transport model, *Zeitschrift für Geomorphologie* 29(2): 193–211.

Schwab, O.G, Fangmeier, D.D, Elliot, W.J., Frevert, K.R. (2002). *Soil and Water Conservation Engineering* , John Wiley & Sons, Inc. New York: 18–47.

Skempton, A.W. (1953) Soil Mechanics in relation to Geology, *Proceedings, Yorkshire Geological Society*, 29: 33–42.

Skempton, A.W. and Hutechinson, J.N. (1969) Stability of natural slopes and embankment foundation, State of the Art Report, *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering*, Mexico City: 291–340.

Terzaghi, K. (1962) Stability of steep slopes on hard unweathered rock, *Geothnique*, 12: 251–270.

Van Burkalow, A. (1945) Angle of repose and angle of sliding friction: An Experimental study, *Bulletin of Geological Society of America,* 56: 669–707.

Wallace, R.E. (1977) Profiles and ages of young fault scarps, North-Central Navada, *Bulletin of Geological Society of America,* 88: 1276–1281.

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