MECHANISM OF GULLY-HEAD RETREAT - A STUDY AT GANGANIR DANGA, PASCHIM MEDINIPUR, WEST BENGAL

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Abstract

Twenty three gully heads were randomly selected from a representative gully basin at Ganganir Danga, Paschim Medinipore West Bengal for understanding mechanism of gully head retreat. The study was made during June to September, 2011. Height and slope of gully heads, width at top and base of the gully head were monitored. Geotechnical properties of soil like cohesion and angle of internal frication, bulk density were measured to estimate shear stress and shear strength at gully head. Linear retreat of the gully heads was monitored by pegging technique. Depths of tension cracks were measured at regular interval. The study shows that, gully heads retreated at different rates ranging from 13 cm to 121 cm depending on instability factors. Gully heads are few times steeper than angle of internal friction that introduces instability. Alcove structure and plunge pools, developed at the bottom of gully heads, lead to formation of overhanging slope. Near vertical and overhanging slope of considerable height develop tension cracks leading to mass failure and gully head retreat. Number of instability factors is operating at the gully heads and no linear relation can be established between these factors and gully erosion.

Key words: *Tension crack, Mass failure, Gully head retreat, Geotechnical properties.*

Introduction

Gully erosion, caused by the instability of the channel or gully-heads and gully-walls, is a serious problem in lateritic environments and is responsible for the destruction of agricultural land and structures such as roads, bridges and pipelines. Gully erosion produces large volumes of sediment that are transported downstream with detrimental effects on water quality, reservoir capacity and floodplains (Bryan, 1990; Poesen *et al.,* 2003; Wells *et al.,* 2009, 2010). In any channel network, approximately half of the total length of channels lies with un-branched fingertip tributaries (i.e. first-order). Environmental changes that induce catastrophic rains promote channel extension and have, therefore, a very large potential impact on the landscape. During discharge events channel heads may advance great distances upland, or retreat down slope if the hollow refills. In extreme cases, gullies can grow in length by tens of meters per year, and may also incise their channels, creating steep ravine banks. One possible end result of these processes is the creation of badland areas, where there is little or no remaining land that is suitable for agriculture. A large number of field studies have demonstrated the channel heads and processes controlled by channel initiation under different environmental condition (Dietrich *et al.,* 1992; Montgomery and Dietrich, 1989, 1992, 1994; Dietrich and Dunne, 1993). A large variation in this channel head and process is observed, depending on many factors (i.e. source area, source basin length and contributing area per unit contour length) (Abrahams, 1984; Dietrich *et al.,* 1992; Montgomery and Dietrich, 1989). The location of heads on steep slopes is controlled by subsurface flow, instability of colluvial fill, whereas on gentle slopes, head location is governed by overland flow (Montgomery and Dietrich, 1989; Montgomery, 1999). Bradford and Piest (1985) investigated that the gully head is related to both the timing and nature of gully sidewall failure.

Gully network expansion is mainly caused by gully-head retreat and gully-walls erosion (Ghimire *et al.,* 2006) which is a complex process with interactions and feedback mechanisms that are only conceptually and qualitatively understood (Oostwoud Wijdenes

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and Bryan, 2001; Menendez-Duarte *et. al.,* 2007). Processes of gully-head retreat and gully development include upslope movement of the gully-head, hydraulic shear by overland flow on the rim and on the vertical walls, the impact of splash or a plunge pool at the foot of a headcut, and mass wasting of walls, due to the development of tension and desiccation cracks, seepage erosion, tunneling and headward migration (Oostwoud Wijdenes *et al.,* 1999, 2000, 2001).

In analyzing the stability of gully heads and walls formed in the laterite soils of the Western part of West Bengal, a range of factors were considered such as degree of slope, slope height, soil density, and soil strength. Failure of a cohesive soil with internal friction is assumed to be adequately described by the Mohr-Coulomb theory. In the present study, attention has been given to the mechanics of gully-head retreat through geotechnical analysis of the structural instability of the materials. Main objective of the study includes understanding of mechanism of gully head extension in the study area as an interplay of the factors.

Material and Methods

Study Area

Ganganir Danga (22° 51´ 18″ N to 22° 51´ 30″ N and 87° 20´ 20″ E to 87° 20´ 28″ E) is located at Garbheta in Paschim Medinipur, West Bengal. One of the main characteristics of the study area is the dissection of the landscape by a dense and deep network of gullies. Inter-gully areas are usually undulating to rolling. The average slope angle of the study area ranges between 5º and 60º. The maximum depth of gullies varies between 10 and 20 m. The cross-sectional shapes of the gullies are V or U shaped, with maximum sidewall slope angles of 85º (mean 63 º, Standard deviation 16.4, n=79). The study area experiences tropical monsoon climate having a prolonged dry period. Annual rainfall about 1428 mm and almost 70% of total rain concentrates in monsoon period. Temperature varies from 48° C (May-June) to 10° C (Dec-January). Soil is mainly sandy or sandy loamy in type. Geologically this region is the western margin of Bengal Basin and represents the characters of a plateau fringe. Cross beddings and parallel beddings, composed of the grains of varied size shows possibility fluctuation in erosional environment (Dey *et al.,* 2009)

Sampling

Twenty three active gully heads were randomly selected for measurement of gully head dimensions in relation to fixed points (pegs), and the survey has been conducted during initial pre-wet season and end of wet season, 2011. At each gully head, different geometric variables like depth of gully head, slope gradient (SD) and length of recession (LR) were measured by clinometers and measuring tape respectively. The changes in the plans and dimensions of the gully heads have been used to estimate the amount of sediment volume eroded and the surface area affected. Field observations were also undertaken during the wet seasons to assess processes and factors of headscarp recession.

Soil samples from twenty three sites were collected by cylindrical core during monsoon season (Table-1). The laboratory tests were conducted in Geography Laboratory of Vidyasagar University and Geotechnical Laboratory of Geological Survey of India (GSI), Kolkata. The testing procedures were in accordance with Indian Standard Method of Test of Soil (Part-XV), 1965. Bulk Density and unconsolidated shear strength (λ) and shear stress (τ) were estimated by Triaxial Compression Test (Casagrande, 1936; Terzaghi, 1942).

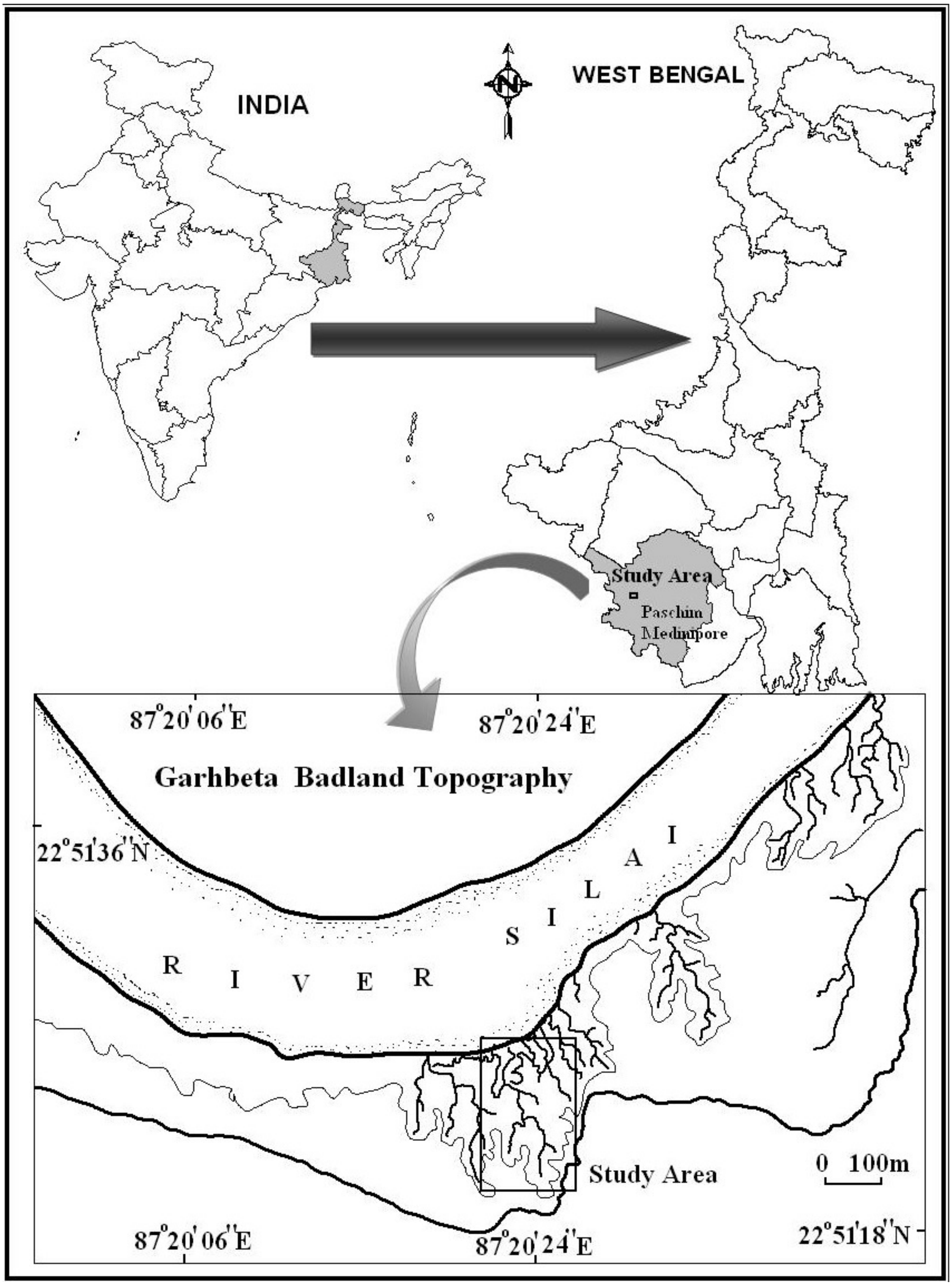

Figure1 Location of the Study Area

Results and Discussion

Mechanism of Gully Head Erosion

Three processes of gully head erosion with an aerated overfall were observed: (i) surface seal failure at the headcut brink-point, (ii) soil washout along the aerated headcut face, and (iii) plunge-pool scour (Figures 3 B, C and D). During overland flow, the intermittent removal of pieces of surface seal was observed at the headcut brink-point (Figure 3A). These pieces were hexagonal to rectangular in shape, approximately 1 to 10 mm in length, several millimeters wide, and about a millimeter thick. Once a piece of seal was removed, the under-laying soil was quickly washed away. At the scarp margin, numerous cracks were observed on the exposed soil surface, parallel to the headcut and transverse to the flow direction. These cracks were (i) arcuate in shape, discontinuous across the exposed bed of the soil, and normally centimeters long, (ii) widest and deepest near the brink-point, becoming faint and shallow further upstream and (iii) restricted toe distance of approximately 20 to 30 cm from the headcut brink-point. Crack formation in surface seals could be related to turbulent shear forces; subsurface pressure effects particularly tension (Romkens *et al.,* 1997) and cantilever mass failure of the soil.

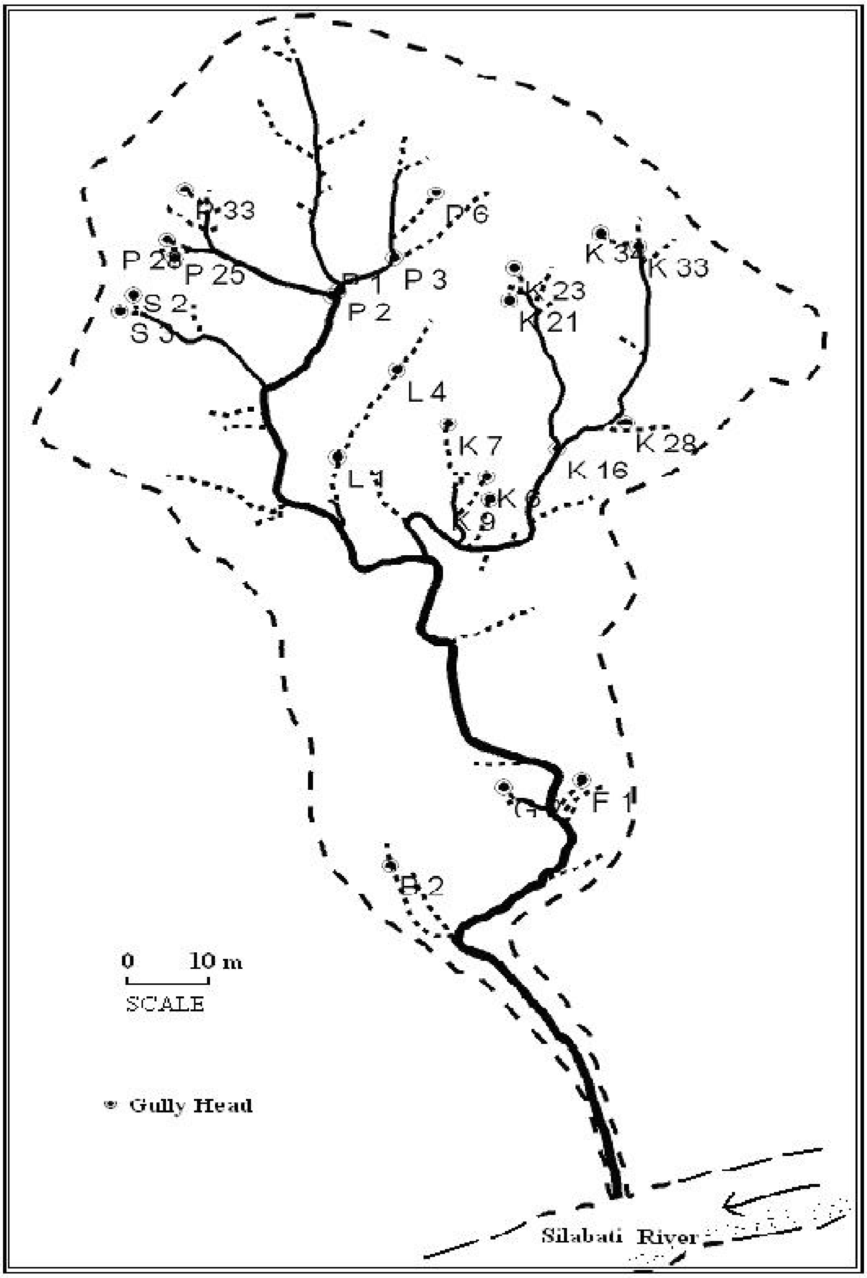

Figure 2 Large Scale Map of the concerned gully showing the sample gully heads

Gully developments have been found to occur in three phases: (i) failure of gully head and gully banks, (ii) transport of the debris by stream-flow, and (iii) degradation of the channel. Gully erosion is impeded by limiting any one of the three phases. The process is associated with the energy generated by water falling over the headcut and flowing down the channel. If the energy of the flowing water is concentrated at the gully headcut, large masses of soil will be eroded (Figure 3). Terraces use to decrease the water overflow energy by increasing infiltration into the soil profile (Bradford, *et al,*. 1973). Also, if the sediment load of a stream exceeds the stream's ability to carry the load, sediment will be deposited and erosion of banks and beds will be retarded. In the process of gully erosion, the resisting forces of the gully walls decrease to a point at which safety factor becomes less than one and the situation leads to collapse of the steep gully wall and gully heads. With this slumping of the near-vertical slope, more stable slope geometry is formed. Gully head advance generally occurs in this manner after the peak overland flow discharge coincides with maximum piezometric response at the base of the headcuts. After failure of a block of soil from a headcut, root reinforcement of the near-surface soil usually maintains an overhanging lip of soil. These overhanging masses collapse later in the season when desiccation cracks develop from their base up to the ground surface. Bradford and Piest, (1985) investigated that basal headcut failure occurs due to collapse of the overhanging mass (Figure 4).

The entire 23 sample gully heads registered remarkable retreat head ward (Table 2). Rate of retreat depends largely on the instability factors operating at each head. Instability results due to interplay of height, gradient, pressure of tension crack, depth of tension crack, angle of internal friction etc. Gully head B2, P1 and K33 registered maximum headward retreat due to more height and gradient. The gully heads like K7, K28, K23, S2, P33, P6 showed maximum height and slope, but could not attain maximum retreat. Instead of having maximum linear retreat, gully head B1, P1 and K33 did not register maximum area extension, as the circular dimension of alcove on gully face in restricted. Thus no linear relation could be established between these factors and gully head erosion (Table 1 and 2). A complex interplay among these factors occurs and a further detailed study is required to understand the relative importance of any of these factors (Figure 5).

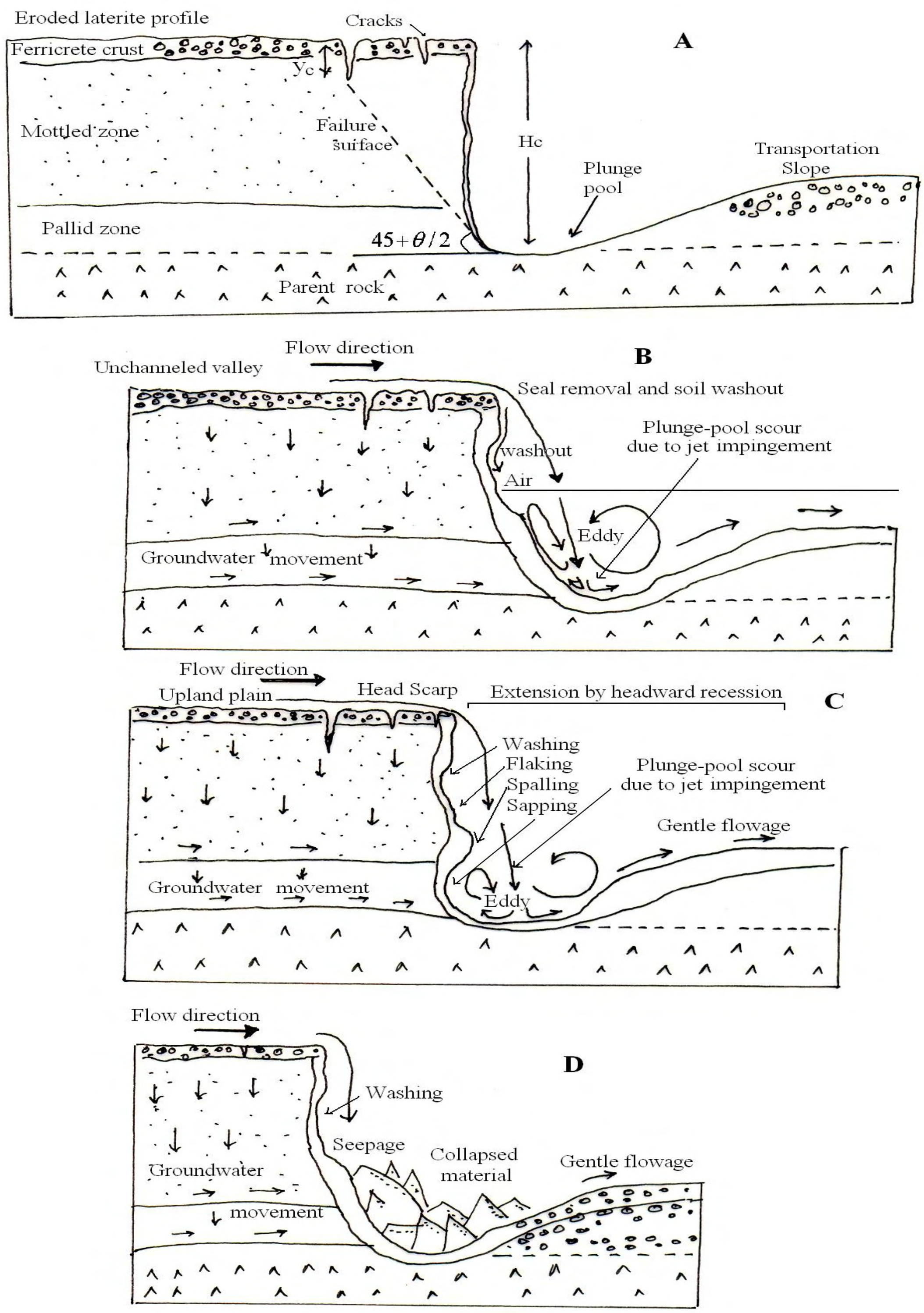

Figure 3 Schematic diagram of gully head. (A) Critical stable height (Hc) of headcuts subject to undermining by plunge-pool erosion and to weakening by cracking to a depth (yc), during dry periods. (B, C, D) Stages of gully head development and migration process

Figure 4 Overhanging mass at gully head, tensional crack and plunge pool

Geotechnical Properties of Gully Stability

The soil texture, bulk density and safety factor are most important geotechnical parameters in determining gully head or gully wall stability and potential for gully head advancement. From compaction tests result, the maximum and minimum bulk densities of gully head soil are found to be 2.68 g/cm^{3}and 1.68 g/cm^3 respectively.

Effect of Friction Angle on Gully Stability

The stability of gully-heads and gully-walls is strongly dependent on other factors, such as angle and height of gully wall (Bull and Kirkby, 2002; Poesen *et al.,* 2002), structural instability of the materials (Collison, 2001). Generally temporary stability of dry materials is achieved at angle of internal friction that is almost equal to repose angle. In all the sample gully heads, angle of friction is lower than the slope of gully head (Table-1). This difference in slope angles introduces internal instability to the system that in turn, induce slumping and failure.

Table 1Gully head geometry and geotechnical attributes during monsoon period

Name of the Gully Head	Location	Height (cm)	Slope angle (deg)	Depth of tension cracks (cm)	Bulk density (g/cm3)	Cohesion (C)	Internal friction (θ)	Safety factor= shear strength (λ)/ shear stress (τ)
K9	22°51'27.2"N&87°20'26.6"E	40	74	4	2.22	0.31	23.32	0.9027
K7	22°51'26.8"N&87°21'22.8"E	130	95	3	2.14	1.19	21.97	0.9160
K6	22°51'26.9"N&87°20'22.6"E	130	87	5	2.22	0.90	28.00	0.9441
G2	22°51'29.0"N&87°20'22.7"E	25	75	10	2.25	0.80	27.24	0.9543
B2	22°51'28.1"N&87°20'22.6"E	145	74	12	2.68	1.42	21.28	0.9194
L1	22°51'27.2"N&87°20'23.5"E	72	78	11	2.43	0.69	18.48	0.9538
L4	22°51'26.7"N&87°20'23.4"E	80	55	7	2.06	0.34	27.42	0.9754
F1	22°51'28.7"N&87°20'22.3"E	35	76	9	2.22	0.16	31.20	0.9558
P2	22°51'25.7"N&87°20'23.7"E	62	78	6	1.87	0.55	26.52	0.8682
P1	22°51'25.7"N&87°20'23.7"E	110	83	5	1.94	0.15	30.61	0.8121
K28	22°51'26.6"N&87°20'21.9"E	220	90	3	2.01	0.26	26.14	0.9015
K34	22°51'27.3"N&87°20'22.0"E	50	70	5	2.40	1.21	30.22	0.9801
K16	22°51'26.6"N&87°20'22.4"E	72	84	7	1.68	1.34	24.30	0.9420
K23	22°51'25.9"N&87°20'22.4"E	250	92	9	1.78	0.85	25.41	0.9142
K21	22°51'26.0"N&87°20'22.6"E	75	90	12	1.99	0.67	28.12	0.9450
K33	22°51'26.4"N&87°20'22.3"E	105	64	11	1.87	0.94	32.16	0.9814
S2	22°51'26.0"N&87°20'25.2"E	190	88	16	2.01	1.11	30.10	0.9721
S3	22°51'26.2"N&87°20'24.9"E	170	65	10	2.31	1.34	29.42	0.9630
P28	22°51'25.7"N&87°20'24.2"E	400	70	8	2.24	1.01	30.78	0.9142
P25	22°51'25.6"N&87°20'24.4"E	105	85	6	2.12	1.20	21.84	0.9104
P33	22°51'25.4"N&87°20'24.3"E	450	86	9	2.10	1.34	23.61	0.9230
P6	22°51'25.2"N&87°20'23.1"E	380	55	8	1.84	1.35	31.30	0.9715
P3	22°51'25.6"N&87°20'23.3"E	60	65	5	1.89	0.51	26.55	0.9312

Effect of Tension Cracks on Gully Stability

Tensional cracks tend to decrease the overall stability of the gully-head and gully wall by reducing cohesion and, when these cracks are filled with runoff water, the pore water pressure increases dramatically, often resulting in failure or contributing to toppling (Collison, 2001; Bull and Kirkby, 2002). In this respect, the presence of tension cracks in gully-head and gully side-walls are indicators of gully widening (Collison, 2001; Oostwoud Wijdenes *et al.,* 2000). Tension cracks development is also influenced by undercutting of gully-walls and gully-heads. Processes like plunge pool erosion, destruction flutes followed by debris erosion, or undercutting of flutes by concentrated flow accelerate wall failure (Oostwoud Wijdenes *et al.,* 2000; Collison, 2001; Vandekerckhove *et al.,* 2001; Poesen *et al.,* 2002; Martinez-Casasnovas *et al.,* 2004). Tension cracks would develop between 30 and 50 cm upslope from the gully-head or gully-wall when desiccation and tension stresses play in combination and the condition would increase the through-flow velocity in the gully-head or gully wall, promoting collapse (Figure 4).

Table 2 Gully head change during study period

Name of the Gully Head	Linear Retreat (cm)	Area (Cm^2) on 30.06.2011	Area (Cm^2) on 11.09.2011	Gully head Area Extension (Cm^2)
K9	24	38	46	8
K7	15	17.8	20.2	2.4
K6	72	58	108	50
G2	24	34	64	30
B2	121	10	64	54
L1	12	56	71	15
L4	14	89	101	12
F1	20	7.6	9.2	1.6
P2	23	15	38	23
P1	100	9	33	24
K28	78	65	94	29
K34	75	25	53	28
K16	19	33	37	4
K23	65	64	108	44
K21	61	33	66	33
K33	110	37	86	49
S2	32	43	56	13
S3	43	34	51	17
P28	45	28	47	19
P25	40	35	59	24
P33	34	89	125	36
P6	64	21	52	31
P3	13	22	32	10

Figure 5 Alcove resulting from basal gully headcut failure in July, 2011. Note the displaced pedon resting at the base of the headcut, the seepage face on the headcut, and the overhanging slope on the top half of the headcut

Conclusion

Gully head retreat and gully bank instability may also depend on factors other than those included in this study, such as seepage of subsoil water, changes in electrolyte concentration of the soil solution, and wetting and drying cycles. Some of these factors may be incorporated into our analysis if their effects on the mechanical and hydraulic properties of the soil are known. Other factors such as seepage will necessitate a more complicated analysis of gully wall stability involving horizontal as well as vertical variations in the mechanical properties of the soil mass. The instability factors have been monitored for one rainy season only. As such, it is difficult to establish a relation between these process factors and gully head responses. A complex interplay of a number of factors may lead to the instability and resultant retreat of gully head. The present study leads to the understanding of linear working of some of the processes. A long continued study with sophisticated techniques for monitoring piezometric pulse at gully head during rain, seepage of water and sediment, mechanical and chemical change of the soil at gully head in response to temperature and moisture flux may lead to detailed understanding and concrete inference.

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