DIVISION S-5—SOIL GENESIS, MORPHOLOGY, AND CLASSIFICATION

Failure Sequence of Gully Headwalls in Western Iowa[1]

J. M. Bradford, R. F. Piest, and R. G. Spomer[2]

ABSTRACT

A characterization of the failure sequence of gully headwalls and banks is necessary to predict gully erosion rates and to develop controls. A model is given for the sequential nature of gully growth in the thick loessial area of western Iowa. The failure sequence includes a popout or alcove failure near the toe of a near-vertical wall, columnar sloughing of the overhanging material, and finally the transport of the eroded material downstream. The initiating failure at the base of the wall is a result of weakening of the soil material by wetting. The gully bank failure sequence and geometry in the western Iowa loess region is compared to gully erosion studies in the glacial drift region of northwestern Missouri and in the Piedmont of South Carolina.

Additional Index Words: **soil strength, soil morphology, erosion, sedimentation, slope stability, groundwater, loess, alluvium, geomorphology, soil structure**

THE GULLY CYCLE of cut-and-fill is endemic to landform evolution in the thick, friable loess mantled topography of western Iowa (Daniels, 1966). Ruhe (1967) presumed that the gully cycle in western Iowa postdates the Late-Wisconsin age. Relying on conclusions of Lane (1931),

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[2] Soil Scientist, USDA-ARS and Dep. of Agronomy, Univ. of Missouri-Columbia; Hydraulic Engineer, USDA-ARS, Columbia, Missouri; and Agricultural Engineer, USDA-ARS, Council Bluffs, Iowa, respectively.

Ruhe hypothesized that a change in the climate from cool, moist conditions of the coniferous period [11,600 years before present (YBP)] to a warm, moist environment of deciduous forms (8,170 YBP) prepared the landscape for gullying. A gradual drying of the climate creating the grassland environment (6,570 YBP) resulted in stabilized gullies. Daniels (1966) speculated that the Recent but presettlement gully cycle must be less than 800 years old and that there were no exposed gullies when the western Iowa loessial region was settled about 1850. Yet, the cut-and-fill presettlement history of alluvial fill in Harrison County, Iowa (Daniels, 1966) would suggest that Recent gullying might even date to 2,000 YBP.

Accelerated erosion often accompanies settlement of an area, especially if the natural cover is replaced by clean-tilled crops. This greatly increases peak runoff rates causing gullies to develop along field boundaries, farm lanes and roads, fence rows, in cattle trails, and along valley-slope drainageways. Post-settlement evidence of gully erosion in the Treynor, Iowa, watersheds is the occurrence of barbed wire, fence posts, and animal bones cropping out of alluvial deposits along newly eroded gully walls. According to Allen,[3] from 1938 to 1944 the number of gullies on the west-facing slope of a 42-ha watershed increased from 5 to 14.

Blong (1970) stated that the exact number of cut-and-fill cycles at any one site would never be known from the sediment record, since any instability period resulting in excessive gully widening could remove evidence of earlier cut-and-fill cycles. Thus if studies were restricted to areas of extensive gullying, older cut-and-fill cycles would no longer be distinguishable.

Large gullies can develop rapidly; whereas many years are required for deposition sufficient to fill such depressions. In western Iowa, Daniels (1966) reported that an overnight 13- to 18-cm rain in a 1-ha watershed opened a small drainageway forming a gully 21.9 m long, 2.4 m deep, and 2.4 m wide at the top.

Gullies develop by stages, and these stages have been described in differing levels of detail by Woodruff (1935), Ireland et al. (1939), and Daniels (1966). Ireland et al. (1939) proposed: (i) channel erosion by downward scour, (ii) headward cutting and rapid enlargement, (iii) healing, and (iv) stabilization. In this paper, we restricted our discussion to bank slumping (the second stage) and did not dwell on further growth mechanisms, like the cleanout process. The gully headcut will continue to advance if the fallen debris is removed by runoff.

In the following discussion of the growth of the headcut and failure of the walls, we will identify the gully failure sequence and causes of that sequence in the western Iowa, Treynor watershed gullied area. We will relate our Treynor, Iowa, watershed studies (Saxton and Spomer, 1968; Piest and Spomer, 1968; Piest et al, 1975a; Piest et al, 1975b; and Bradford and Piest, 1977) to the gully erosion findings of Woodruff and Smith (1938) on the glacial drift region of northwestern Missouri, of Ireland et al. (1939) on the Piedmont of South Carolina, and of Daniels (1966) on the loessial region of western Iowa. We will also relate the mechanisms of headwall and bank erosion to the geomorphology, stratigraphy, and soil structure of the three regions and describe gully geometry difference between regions.

Fig. 1—Large alcove failure along gully bank.

DISCUSSION

Failure Sequence

From observations from controlled gully wall failure studies and from collecting sediment samples during runoff events in western Iowa, our conception of the failure sequence of headwalls in loess or loess-derived alluvium is, in general, as follows:

1) An alcove or popout failure takes place near the toe of a near-vertical wall. As described by Lutton (1969), both alcoves and popouts consist of pyramidal blocks freed from the wall by one fracture inclined into the slope and a second fracture below inclined out of the slope. Popouts are localized low on cut faces but above the base in distinction from alcove failures. Bradford and Piest (1977) pictured an alcove-type failure during a field modeling study simulating gully wall development. The early stages of a much larger alcove are seen in Fig. 1. The alcove or popout failure seems to be the seat of bank instability. The exact mechanism of this undercutting failure is not certain; however, most likely saturation of the soil at the base of the slope weakens the loess and results in a greater tendency toward consolidation, thus putting the soil above the wet layer in tension and producing the arched caving failure surface (Sheeler, 1968; and Handy, 1973). There is no indication of bulging occurring at the slope base, and seepage forces exerted by the flowing groundwater do not have a significant effect on the popout (Bradford and Piest, 1977).

2) Columnar sloughing or failure of the overhanging material occurs because the soil is in tension. A sliding

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[3] W. H. Allen, Jr. 1971. Landscape evolution and soil formation—Treynor, Iowa. Ph.D. Thesis. Iowa State Univ., Ames, Iowa.

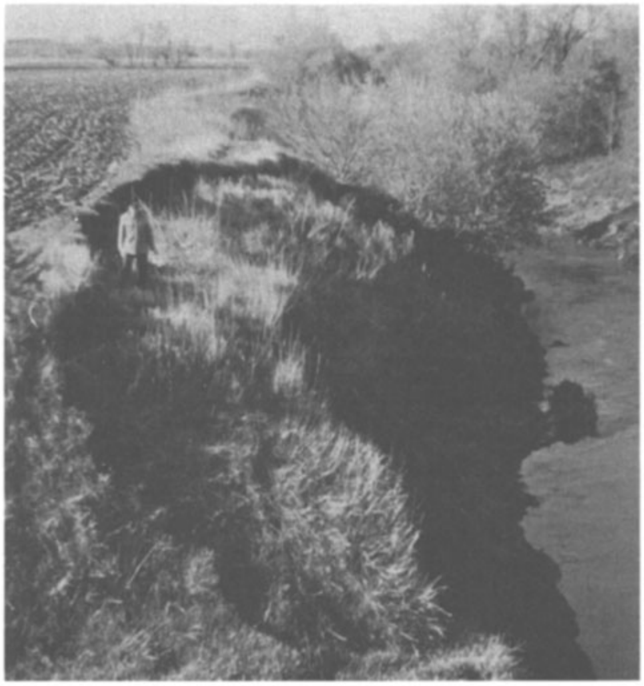


Fig. 2—Rotational failure in loessial soils.

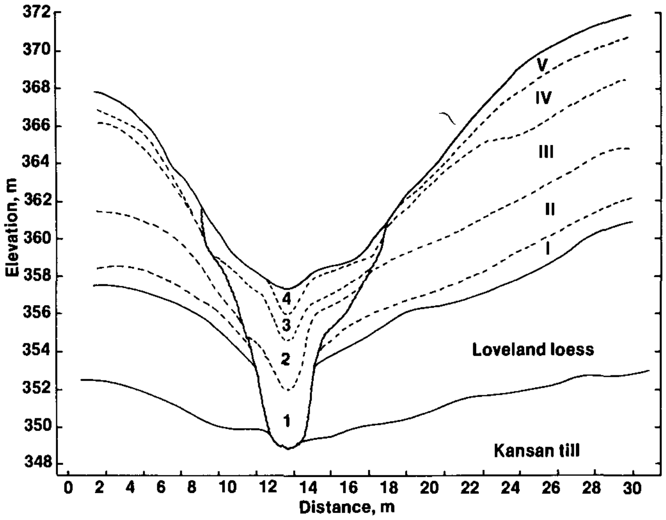


Fig. 3—Stratigraphic cross section typical of the western Iowa, Treynor watersheds. Generalized diagram based on studies of W. H. Allen, Jr. and show the members of the DeForest formation *alluvium* (4-Turton, 3-Mullenix, 2-Hatcher, 1-Watkins) and different zones of Wisconsin loess (V-solum, IV-noncalcareous, III-calcareous, II-calcareous, and I-basal Wisconsin loess).

surface does not form, and the failure surface most likely occurs along pre-existing cracks. In falling, the loess normally breaks up, obscuring the alcove or popout failure. The debris which falls to the slope base tends to clog internal water flow within lower layers of the slope and cause a build up of the pore water pressures behind that area of the slope. However, since the slope angle has been decreased by the debris, the slope increases in stability. Rainfall and runoff are not necessary to initiate the first two steps. A slow increase in the water table or a decrease in soil strength due to surface infiltration may contribute to the failure several days after rainfall.

3) Finally, the eroded material is entrained and transported downstream by runoff, allowing the sequence to be repeated. If the runoff is insufficient to transport the fallen material, the sequence is interrupted and some measure of channel bank stability is attained.

Neither the popout or alcove failure nor the columnar sloughing are unique to loessial soils. As noted by Lutton (1969), these processes are quite common in rock slopes. Failure of rock slopes is generally controlled by fractures or bedding plane weaknesses which define the failure path. Likewise, the deformation properties and structural features of each soil layer or horizon influence the size and manner of the failure and contribute to the discrepancy between observed and predicted stability.

Ireland et al. (1939) found a similar cycle of gully head caving in residual Piedmont soils derived from weak parent material. A vertical or near-vertical headwall condition with little or no overhang was followed by an undermining of the saturated, weak, C horizon by erosion or caving due to back trickle, seepage, or spray. Also, the gully floor showed lowering from the action of the plunge-water. These processes resulted in the collapse of the overhang.

Daniels (1966) did not observe undercutting during runoff in the Harrison County, Iowa, area and stated that even though some headwalls were undercut, it was not a normal feature of most headwalls. Daniels also found no sapping at the base of gully walls by emerging seep water and no evidence of seepage surfaces on the gully walls. Little difference was observed in the movement of nickpoints upstream and the mechanisms of gully headwall advance; however,undercutting, was observed during periods of headward movement of nickpoints. He thought undercutting in entrenched streams in alluvium was the result of wave action removing the fine material from the base of the nickpoint.

Downstream from the gully head where the banks are less vertical, the processes outlined above are not prevalent. Under extreme wet conditions, a deep-seated, circular, rotational failure surface, such as shown in Fig. 2, may occur.

Gully Geometry in Relation to Soil Stratification

Within the western Iowa-Treynor area watersheds, the major Pleistocene deposits are Kansan till, Loveland loess, and Tazewell loess (Fig. 3). Post-Wisconsin alluvial fill, defined by Daniels and Jordan (1966) as the DeForest Formation, occupies all the drainageways. Relative soil strengths, permeabilities, thicknesses, and structural features of these deposits influence gully wall geometry and the rate of gullying.

Gully development entirely within Recent alluvium is strongly influenced by the soil surface member (Fig. 3), the structural features in that member, and by the alluvial members present in relation to the loess or till below. From their gully model study in western Iowa, Bradford and Piest (1977) found that the higher strength and density of the Mullenix member of the DeForest formation alluvium (Fig. 3) controlled the depth of gullying at the model study site. The shape of the failure surface was controlled by the vertical structural units in the upper alluvial member, designated as the Turton member.

Within Treynor watershed no. 3, the Soetmelk mem-

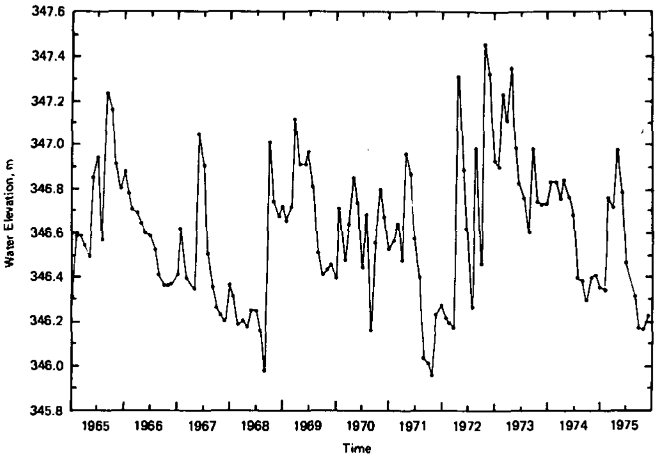


Fig. 4—Seasonal variations in piezometric level about 18 m from headcut of watershed no. 1 near Treynor, Iowa.

ber—a calcareous sand and gravel layer of low density and strength—was encountered by Allen[3] about 30-m upslope from the present gully headcut. Gully growth would probably accelerate after it enters this low strength material because of rapid failure at the toe of the wall. When gullies erode through alluvial members and reach the Kansan till, the greater strength, higher clay content, and low permeability of the till limit gully development.

Rapid growth would also occur if gullying were proceding within Tazewell loess (0–1.5 m), overlying a Tazewell alluvium (1.5–1.8 m) of sandy texture (Daniels, 1960) and a Tazewell till (1.8+ m). The 30-cm zone of weak sand would accelerate gully development, while the greatest resistance would be from the till.

In certain cases, small gullies have developed entirely within Tazewell loess. As within alluvium, various zones or horizons have been designated and the gully geometry is dependent upon the mechanical properties of these zones. Ruhe (1954) described weathering zones in Tazewell loess in southwestern Iowa from the surface down as: oxidized and leached; deoxidized and unleached; oxidized and unleached; and deoxidized and leached. Allen[3] recognized many localized exceptions, particularly on side slopes and in high, eroded positions. Daniels (1960) observed that small gullies have a vertical headwall in calcareous loess but not in leached loess. This phenomenon stresses the importance that calcium carbonate plays in the mechanical cementation of the internal structure of loess. Turnbull (1968) supported this concept. Leached loess of western Iowa contained very little calcium carbonate (generally < 1%; Allen[3]) and did not stand on vertical slopes as well as unleached loess with a calcium carbonate equivalent of 3 to 6% and in some instances, 8 to 10% (Allen[3]).

In the early 1930's at the USDA Experiment Station at Bethany, Missouri, gully formations were examined and controls were formulated for soils formed from unweathered Kansan till (Woodruff and Smith, 1938). Active gully development was within areas of Shelby loam (fine-loamy, mixed, mesic Typic Argiudolls). The C horizon composed of compact glacial till has moderately slow permeability. Gullies with vertical headcuts and V-shaped bottoms develop as the gully becomes incised in the more resistant, higher strength till.

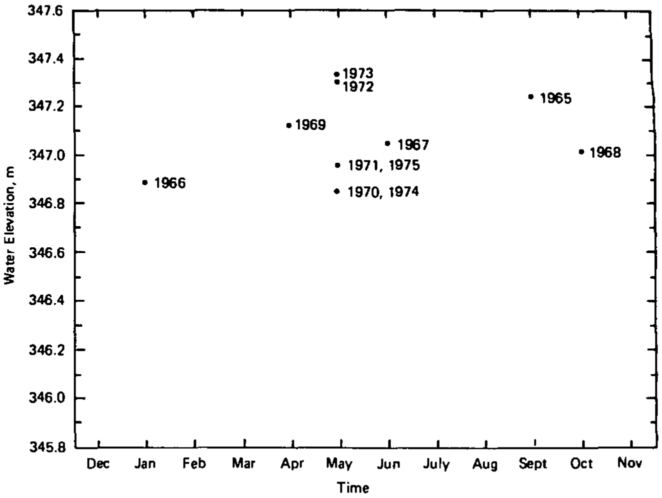


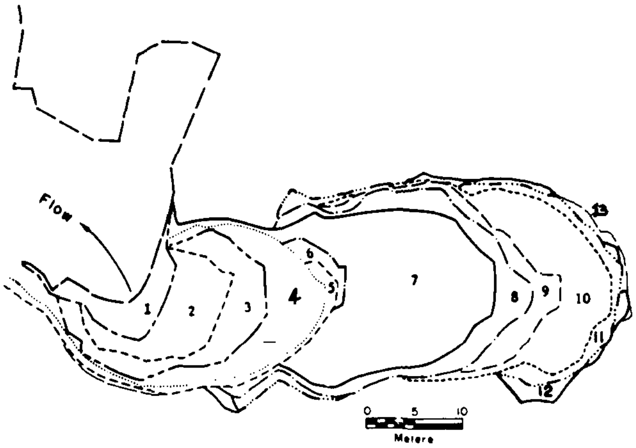
Fig. 5—Relation between elevations of annual peaks in piezometric level of watershed no. 1 near Treynor, Iowa, and their date of occurrence.

Ireland et al. (1939), who were concerned with gully growth mechanisms in the southern Piedmont region of South Carolina, found that the character and thickness of the C horizon was of prime significance in determining the progress of gully cutting. The upland soils of the Piedmont are formed from residual soil materials derived from the underlying or upslope rock. Deeply weathered rocks had potentially deeper channels. Under conditions of thick C horizons composed of rotten rock 3 to 15 m deep, deep U-shaped gullies develop quite rapidly. Many of the gullies in the Cecil series (clayey, kaolinitic, thermic Typic Hapludults), an extensive series in the upper (western) part of South Carolina Piedmont, are 6 to 9 m or more deep. Not all gullies on the Cecil soil have the characteristic U-shape. If the B horizon is unusually thick and clayey, a V-shaped gully similar to those in the Kansan till at Bethany, Missouri, evolves unless the depth of downcutting gets below the B horizon.

Groundwater Conditions

The depth to water table in relation to the geometry of the gully bank plays an important role in the stability of the wall and sequence of failure. The position and contour of the water table influence gully wall failure since (i) soil strength decreases with increasing moisture content, (ii) the effect of seepage forces along the potential failure surface depends on their direction, and (iii) the increased unit weight of the soil mass with greater water content exerts more force. The failure of the gully wall is not a direct function of groundwater level, since other variables, as discussed later, also influence gully wall stability.

Long-term observations in groundwater wells in the gully study area near Treynor, Iowa, give the seasonal fluctuation of piezometric levels. Fig. 4 shows the elevation of the peak monthly piezometric level in a groundwater well located about 18 m to the side of watershed no. 1 headcut. Annual peak piezometric levels and the month they occurred are plotted in Fig. 5. This shows a marked tendency for the annual peak elevation to be higher during the spring months when most of the gully erosion occurs (Piest et al., 1975a). In some years, the largest amount of



Area	Period	Areal change	Surface runoff	Gully erosion
		meters^2	meters^3	tons (metric)
1	15 Nov. 1964–14 Apr. 1965	44	30,600	120
2	15 Apr. 1965–9 June 1965	78	21,000	460
3	10 June 1965–13 Aug. 1965	86	14,800	140
4	14 Aug. 1965–15 Nov. 1965	116	17,300	320
5	16 Nov. 1965–15 July 1966	36	4,930	80
6	16 July 1966–30 May 1967	12	1,230	<10
7	31 May 1967–27 June 1967	275	86,400	1,310
8	28 June 1967–31 Dec. 1969	90	29,600	210
9	1 Jan. 1970–15 Dec. 1970	54	16,000	160
10	16 Dec. 1970–8 Dec. 1971	131	38,200	360
11	9 Dec. 1971–15 May 1972	57	7,400	310
12	16 May 1972–22 May 1973	52	21,000	60
13	23 May 1973–22 Nov. 1974	11	11,100	70
	Totals	1,042	299,760	3,610

Fig. 6—Measured gully advance and erosion rates, watershed no. 1 near Treynor, Iowa.

gully erosion occurred in the spring, although the peak groundwater level was recorded during other seasons.

Gully erosion cannot be predicted from groundwater well data alone because wall failure depends on slope geometry, soil conditions, and the runoff volume and duration. In 1966, precipitation and runoff were low with the only major storm in June, the month of maximum gully erosion. In 1968, maximum erosion and the peak groundwater level at watershed no. 1 occurred in October. In 1965, 268 metric tons were eroded from the gully at watershed no. 1 in September, the month of peak groundwater level, while gully erosion was 341 metric tons in June, a month with much higher peak runoff rates.

Higher piezometric levels at the headcut are responsible, in part, for the geometry of the massive slumping that occurs near the headcut. Seepage flow volumes measured at various distances downstream from the headcut showed that the amount of seepage per unit area of gully wall was greater near the headcut and decreased downstream. A greater seepage volume implies a higher seepage gradient. Greater seepage forces and an enlarged zone of reduced soil strength increases the stresses causing instability. Downstream from the headcut, little slumping of the walls occurs (Fig. 6; and Daniels, 1966, Fig. 39).

Plunge Pool Action

The development of a plunge pool or scour hole below the headwall influences both the failure shape and rate of headwall advance. Within the vicinity of the headwall and plunge pool, as just noted, seepage outcrops at a higher elevation than downstream, pore pressures are greater, the depth of the wetted zone relative to total height of gully wall is greater, the walls are near-vertical, and the depth from soil surface to streambed is greater. Although the plunge pools are not readily observable during peak flows, their hydraulic performance and effect on gully geometry can be closely estimated.

Table 1—Stability parameters of gully headwalls at Treynor, Iowa watersheds 1 and 4.

Watershed no.	Outflow—1965-1971 Ground water average annual	Surface average annual	Gully erosion average annual	Height (gully floor to soil surface)	Depth (seepage surface from soil surface)	Factor of safety†
	cm	cm	tons	cm	cm	
1	6.4	12.2	446	421	256	0.83
4	15.8	1.7	2	274	110	1.05

† Calculated from the circular limit equilibrium Bishop method of slices (W. A. Bailey, and J. T. Christian. 1969. ICES LEASE-1, A Program oriented language for slope stability analysis. R69-22, Soil Mechanics Publ. no. 235, Dep. of Civil Eng. Massachusetts Inst. of Tech., Cambridge, Mass.).

The total effect of the headwall and plunge pool geometry—and the interaction with seepage and runoff—has often confounded analysis. A higher water table is expected to decrease gully wall stability. However, gully erosion at watershed no. 1 (a 30-ha, continuous corn, field-contoured watershed) has been extreme, while at watershed no. 4 (a 61-ha, continuous corn, level terraced watershed) the gully banks have been stable (Piest et al., 1975a); yet, watershed no. 4 has the higher water table. Gully erosion from 1965–1971 (Table 1) has averaged 446 and 2 tons/year for watersheds no. 1 and 4, respectively. Little gully bank slumping occurred at watershed no. 4 headcut. Furthermore, at watershed no. 4, one would expect a more sloping wall (more stable) in the area of the plunge pool if the runoff were ineffective in cleaning out the fallen debris. Instead, the walls are near-vertical, an indication of debris transport and little bank failure following the cleanout. We are still uncertain as to the exact processes contributing to the stability of watershed no. 4 headcut, but an analysis of the resisting and driving forces within the bank provides an insight into the stability.

A slope stability analysis of the gully walls near the headcuts of the two watersheds was conducted using the circular arc limit equilibrium Bishop method of slices (Bailey and Christian, 1968). Free water surfaces and free water exit points on the exposed gully face were calculated by procedures outlined by Bradford and Piest (1977), using waterwell data 18 m from existing gully walls of both watersheds. The highest water elevations during 1963–1975 were selected to calculate the water pressures within the potential slope failure regions. Soil properties were inferred from measured and assumed values made at watershed no. 3 (Bradford and Piest, 1977; Allen[3]). The 2-dimensional limit equilibrium analyses (Bradford and Piest, 1977) from Table 1 would predict that the headcut at watershed no. 4 is stable even though a high-water table exists. A safety factor of unity or less implies failure and a value greater than unity implies stability. The depth from plunge pool streambed to the upper soil surface at watershed no. 4 does not exceed the critical slope height for the assumed soil and water conditions. A safety factor of

0.83 for a near-vertical wall at watershed no. 1 predicted the resultant instability.

An analysis, like that presented above, overlooks large differences between the two watersheds. The analysis also assumes the mode of failure to be a 2-dimensional circular arc failure.

CONCLUSIONS

A failure sequence of alcoves or popouts, column failure, and cleanout occurs for gully headwall advance in the western Iowa loessial and loess-derived alluvial soils. The initiating failure at the toe of the wall is created by the weakening of the soil material. The structural features of loessial-derived soil promote a columnar slumping of the overhanging material and the reestablishment of near-vertical walls. If a high-strength material were present within the wall, especially at the lower portion, the vertical wall geometry would not develop; this is the case in the gullies formed in glacial till. Thus, the final gully geometry is dependent upon the soil morphology, the type of failure, and finally, the ability of the runoff water to remove the fallen material.

Growth of gullies with unstable walls depends directly on discharge width, depth, and velocity, and sediment load of water within a gully. Very rapid gully growth can occur only if the flowing water has the energy capable of transporting the fallen debris from the base of the wall. The transport process seems to be the limiting factor in the sequence of events.

The sequence and causes of gully headcut advance must be understood before we can thoroughly explore methods to control gully erosion. Management-tillage and conservation systems must be available to control the initiation of gully processes, but the control of further enlargement of existing gullies depends on an adequate balance between reduced runoff and reduced bank slumping. Terraces have been shown to control gully erosion through reduction in runoff; however, there is also a need to investigate lower cost management methods that stabilize bank slumping.

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