Gully Bank Erosion of Loessial Soil in Urbanizing Watersheds

M.E. NICKLIN
University of Nebraska-Lincoln, Lincoln, Nebraska
J.I. REMUS
U.S. Army Corps of Engineers, Omaha, Nebraska
J. CONROY
U.S. Navy Corps of Engineers

ABSTRACT

Problems associated with bank erosion in small urbanizing watersheds in loessial soils were examined. The factors behind the gully erosion problem are hydrologic, hydraulic, and geotechnical in nature. Watershed transitions lead to increased runoff with resulting saturation of loessial soils. Greater scouring velocities also result in accelerating removal of weakened loess. As gully walls develop, slope stability becomes a factor in further widening of gully walls. Gully walls in a surveyed watershed were analyzed according to the Culmann method of slope stability analysis. All slopes indicated stability in an unsaturated condition. If saturated, extremely low factors of safety result for walls suggesting high channel wall instability. Indices were utilized to predict the likelihood of a significant flow's ability to remove failed channel wall material.

INTRODUCTION

Gully erosion is a serious problem in many areas of this country. Damage to property can be very costly as well as unsightly. Gully erosion is a difficult process to analyze and predict. Thus, significant contributions to improved prediction methodology for erosion control are necessary. This study attempts to determine the primary factors behind gully erosion processes in loessial soils which are highly susceptible to all forms of erosion in an urbanizing environment.

Several types of erosion have been identified in the literature. Included are sheet, rill, and gully erosion. Most erosion investigations have concentrated on sheet erosion phenomena, owing primarily to more reliable predictive methodology. In terms of total sediment volume, sheet erosion is generally considered a more significant problem than gully erosion. In some situations though, gully erosion is a more serious problem than sheet erosion. This is especially pertinent when considering stream channel systems situated within urban watersheds undergoing dramatic alterations in hydrologic regime. It is well known that significant changes in hydrologic factors may result in changes in runoff characteristics leading to substantial degradation and aggradation problems within a streamflow system.

Gully erosion has been a difficult subject area to quantify, owing not only to a multitude of geologic variables, but also to the uncertainties of the hydraulic interactions with erodable materials. Finally, there is increasing evidence that the geotechnical factors which have often been overlooked must be considered in gully erosion quantificaiton (e.g. Lohnes and Handy, 1968, and Piest, et al, 1976). Better fundamental insights with respect to the hydrology, hydraulics, geotechnical and other factors of gully erosion are needed in order to provide for better strategies in protecting stream channel systems.

PREVIOUS WORK

The main intent of this study is to define the erosion processes involving loessial soils in ephemeral channels located in watersheds undergoing urbanization. It is useful, however, to briefly review erosion studies involving cohesive soils which have implications to this investigation.

Erosion of Cohesive Soils

Several approaches to erosion analysis in channels with cohesive boundaries have been defined in the literature. Remus (1985) classified these approaches very generally as either empirically, physically, or fundamentally based methods. Most of the literature has been directed toward the empirical methodology although it was suggested that as of late there has been a trend toward more fundamentally based approaches.

The basis of the use of empirical methodology stems from the impracticality of quantifying the underlying mechanisms existing in cohesive soil systems. Included herein are the particle-particle and fluid-particle interaction. It was only feasible to develop logical empirical relationships and then to test the goodness of the model fits rather than develop more physically based methodology. In many instances these models are site specific. Despite difficulties inherent with this approach, some methodology have been successful.

Attempts have been made by some to relate descriptive properties of cohesive soils and flow parameters to erosion rates (e.g. Partheniades and Paaswell, 1970; ASCE, 1968). This literature suggests that the interaction between soil properties and flow variables which control soil erosion is far too complicated to allow for a convenient typification of erosion with general soil classifications or with determination of a soil's composite physical properties. Flow parameters, including mean velocity and average shear stress are still important, however. For this reason more recent investigations have been directed at attempting to integrate the flow variables and soil properties that control erosion.

In general, relatively few discussions predicting velocity effects in cohesive channel sediment erosion seem to exist in the literature with successful results. Most of the work that has been done has been aimed at determining factors associated with preventing deposition rather than preventing erosion. Further, much of this work was intended specifically for canals. One study applicable to natural ephemeral channel systems by Hughes (1980) does deal with scour processes in a range of soil materials. Hughes presented a rather interesting concept of maximum noneroding velocities for ephemeral channels. Hughes defined scour as erosion from the bed or bank and not transport of eroded debris. Channel and flow characteristics from small naturally occurring ephemeral channels in the southwestern United States were measured and statistically analyzed to define representative velocities associated with initiation of scour. Variables selected for the analysis were velocity, depth of flow, and channel bed material. The channel bed material was classified according to the following soil groups: sandy-silt, silty-clay, and clay.

Data from three states, Colorado, New Mexico, and Oklahoma, representative of sandy-silt, silty-clay, and clay soils were plotted on scatter diagrams. With the use of a so-called "asymmetric probability distribution" scour likelihoods on the basis of velocity and depth of flow could be estimated. We found the methodology developed by Hughes possesses potential implications for work initiated in the current investigation involving erosion in loessial soils.

Gully Erosion of Loessial Soils

Most of the work with respect to channel erosion of cohesive soils has centered on those soils containing high clay percentages. Relatively little in the literature could be found defining empirical, physical, or fundamental methodology with respect to gully erosion of loessial soils. Since the erosion problems in many areas (including the current investigation) involve loessial soil it is important that more be learned about stream channel erosion in such soils.

Loess silts belong to a category of collapsible soils found throughout the earth's surface. Generally loess soils are considered to be of eolian origin (in some instances these soils may have been redeposited fluvially or colluvial from eolian sources). Most loess deposits consist of silt-size particles of feldspar and quartz (Mitchell, 1976). A modest percentage of clay (often less than 15 percent) may be present. This clay is generally montmorillonite. Loesses are usually of low density and light cementation which may collapse upon subjection of the material to saturation. Densities of undisturbed loess may be extremely low, even as low as 1200 kg/cubic meter. When saturated, loess soils are relatively strong and incompressible and maintain a porous structure. Once saturated, however, they may be subject to sudden collapse, especially when surcharged. Often, in urban environments, the frequency of saturation and surcharge loadings increases. It is understandable then why the process of occasional bank inundation may be a significant factor leading to degradation in loessial soils.

Piest, et al (1975) did successfully investigate channel and gully erosion of loessial soils in an agricultural environment. Some of the investigative tools of their investigation involving agricultural watersheds applies to the current study which is more concerned with urbanization of agricultural land. On the other hand, there are different considerations involving the erosion processes in the urban versus the agricultural environment. For instance, with land treatment in agricultural areas, infiltration rates can be substantially increased leading to reduced runoff rates and volumes. In the urban environment, however, a different situation usually arises. Typically, surface treatments are eventually implemented as developments are completed which results in reduced land surface erosion products. However, a large portion of the land surface becomes impervious from pavement, parking lot, and roof construction, etc. Thus, infiltration rates will decrease. Therefore, the ability to reduce runoff associated with urbanization is limited without special impoundment construction. The result in some cases is that the most significant form of sediment yield products may be gully erosion products.

Some factors defined in Piest, et al's work relevant to the current investigation include sediment yield-runoff relationships and geotechnical considerations. Piest, el al defined the danger of using traditional sediment-yield runoff rating curves without understanding the geotechnical factors behind accumulations of gully soil debris prior to the significant runoff season. Concentration of available failed bank slope products decreases with the successive spring runoff events. Figure 1 involves a plotting of tabulated data presented in Piest el al of three rainfall events within a 13-day span in May of 1971. The plot indicates the sediment runoff concentrations (as a weighted concentration of the runoff event discharge mass in kg per minute) for the successive events. The use of a computed sediment rating curve on the basis of discharge volume itself would obviously be unreliable in predicting the volume or mass of sediment yield. This discrepancy cannot be explained merely by any difference in magnitude of the discharge since the peak discharge of the third event was

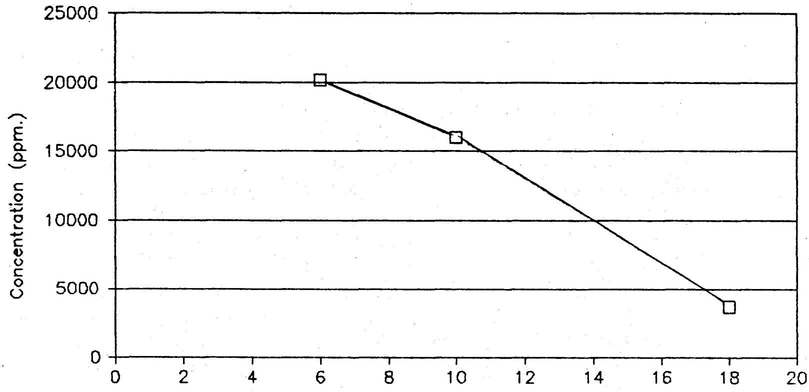


Figure 1. The sediment concentrations (as a weighted concentration of the runoff event) for 3 runoff events in May, 1971 (data from Piest, et al, 1975).

approximately 1.7 times that of the second event. Further, the rainfall intensity and total runoff volume of the third event was greater than that of either the first or second event. Although it is obvious that making interpretations on the basis of only three events in one given year must be treated with caution, the relative importance of event timing is illustrated. This is partially explained by the fact that erosive removal of sediment in loessial gullies involves a large proportion of material from the banks that have failed geotechnically. As the spring runoff events occur sequentially in time, the earlier events have a greater concentration of material in the discharge.

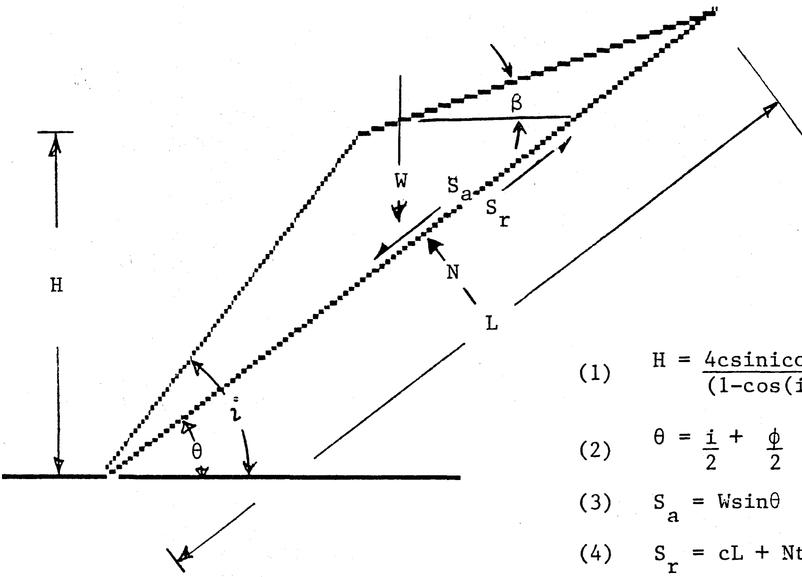
Other factors, in addition to the seasonal timing rainfall events, include both the rate of soil detachment and the sediment transport capacity of the runoff event.

GEOTECHNICAL FACTORS

One area often overlooked in erosion literature involving slopes is the significance of the geotechnical factors. A study by Bradford and Piest (1976) attempted to incorporate the significance of slope stability in erosion by conducting slope stability analyses in loessial soil zones exhibiting gully wall instability and headslope failure features. These failures constitute the primary source of soil debris subject to later tractive force removal. Bradford and Piest (1976) provided crude estimates of slope stability using the simplified bishop method of slices. They hypothesized that the tendency to have slope failure could be estimated by determining factors of safety for various slope conditions exhibiting gullies in loessial systems. Remus (1985) also utilized the simplified bishops method of slices in determining the stability of gully walls following the assumptions of Bradford and Piest.

Bradford and Piest argues for the superiority of the simplified bishops method of slices over other techniques. This claim may be unsubstantiated since Lohnes and Handy (1968) had previously shown the Culmann method as a superior technique for slope stability analysis on steep slopes such as those often exhibited in loessial soils. One reason for this is that failure surfaces on steep loessial soils can be best approximated by planes. The Culmann method uses failure planes versus failure arcs and is thus a better choice when planar failures on steep slopes are involved.

Bradford and Piest attempted to justify the significance of pore



(1) $$H = \frac{4c\sin i\cos\phi}{(1-\cos(i-\phi))}$$

(2) $$\theta = \frac{i}{2} + \frac{\phi}{2}$$

(3) $$S_a = W\sin\theta$$

(4) $$S_r = cL + N\tan\phi$$

(5) $$N = W\cos\theta$$

(6) $$F.S. = S_r/S_a$$

Figure 2. The Culmann method of slope stability stability analysis (Lohnes & Handy, 1968).

pressures in their work. The basis for their inference is related to the existence of so-called "pop-out failures" near the base of the stream channel. However, in general for gullies situated in upland loess, the depth to the water table is such that excess pore pressures are not likely to be involved in the gully wall failure process (Lohnes and Handy, 1968). It is more likely that pop-out failures are related to weakening from high moisture contents in the loessial soil since the sensitivity of loess to moisture content is well known. High moisture contents are more likely near the bottom of the channel.

The Culmann (sliding wedge) method of slope stability analysis is appropriate for high-angle slopes as are typically exhibited in loessial soils. This method involves straight forward application of equilibrium analysis where the ratio of the forces resisting movement S_r to the forces causing movement S_a are determined. When this ratio (the factor of safety) is less than one, instability is indicated.

A graphic of the Culmann method and the appropriate relationships are indicated in Figure 2. The angles Θ, i, β define the failure plane, bank slope, and back slope angles respectively. The ϕ is the internal friction angle. The dimensions L and H are designated in the figure. The unit cohesion index is c. The specific weight is γ. W and N define respectively the weight of and the normal force on the potential failure slab.

Equation 1 is the result of equilibrium analysis and shows that the maximum stable height is independent of the angle of the undisturbed back-slope. Equation 2 is the result of differentiating Equation 1 for c with respect to Θ. Thus the angle depends only on the initial slope angle and the angle of internal friction.

The accuracy of the Culmann method is good for high slope angles i. The accuracy does diminish with decreasing slope angle. For steep slopes in loesses it is preferred to other methods. For lesser slopes other methods including the simplified bishops method may become more reliable.

Tension cracks are important in equilibrium analysis involving steep slopes. The depth of the tension cracks would ideally be determined to improve the accuracy of the slope-stability analysis. Unfortunately, they are difficult to measure accurately in the field. Therefore, it is recommended that tension crack depths be estimated using Rankine indeal-plastic-equilibrium theory (Terzaghi, 1943). The depth of cracking z_o is

$$z = [\ 2c/\gamma\ ]\tan(45 + \phi/2)$$

The importance of the cohesion coefficient in analysis is dependent upon whether or not the loessial soil is saturated or unsaturated. The degree of saturation is important. If complete saturation of loesses occurs then cohesion all but vanishes. Cohesion appears to vary with moisture content in loesses but precise relationships have not yet been established (Lohnes and Handy, 1968).

SELECTED STUDY AREA

The area used in the ongoing investigation involves drainages in urbanized and currently urbanizing sites within the Omaha vicinity. The dominate climate in the Omaha area is subhumid. The average annual rainfall is about 76.2 centimeters with nearly 40 percent of the rainfall occurring in the months of May, June, and July.

The natural watershed channels within the study area in many instances have been modified through replacement with sewers and reconstruction of channels as is typical of many large urbanizing areas. Further, increases in the impervious area from urbanization causes a larger direct runoff volume and a shorter time to peak flow in the channel systems than would exist under natural conditions or agricultural.

The surface geology of the area consists primarily of Pleistocene material overlying the bedrock which is the Dakota Sandstone Formation. The predominant Pleistocene material is a thick layer of loessial material (varying between 30 to 45 meters of thickness). The soils can be broadly divided into two units for engineering pruposes. The break is associated with interglacial Sangamon Soil. This stratisgraphic datum separates the Wisconsinan-age loess from Illinoian-age (Loveland) loess (Benak, 1967).

Three loessial facies have been recognized in this region including an upland phase, a colluvial slope phase, and a valley phase (Condra and Reed, 1950). The upland phase is of concern in this study.

The loess of the Omaha-Council Bluffs is typical of loess everywhere as it is predominately a well sorted silt. With few exceptions the sand content is low and seldom exceeds 5 percent of the sample by weight. What sand is there is in the fine to very fine range. The clay content or clay-size fraction varies by 10 to 40 percent by weight. The mineral constituents of the sand, silt, and clay fractions have been discussed in detail by Daniels and Handy (1959), Ruhe, et al (1966), Castelland (1961) and others. Quartz and feldspars are the two most abundant mineral species of the coarser fraction. The carbonate minerals calcite and dolomite are not as abundant as is typical of loess deposits in the mid-continent. The clay fraction is dominated respectively by montmorillinite and illite.

OBSERVATIONS AND ANALYSIS

Gully erosion is a major problem in the Omaha area. Citizens of the Omaha area as well as officials of several different local agencies have expressed concern over accelerated erosion rates. These concerns address not only the loss of personal property, but also that erosion is causing functional and structural damage to devices such as culvert outlets within the stream channels as well as to other structures along the channel. Additional concerns relate to the aesthetic problems that often result with gully erosion.

Those in authority have attempted to arrest the problem by requiring, when appropriate, the developer to establish a "stable" channel system. This has included attempts at reforming channels (widening channel bottoms and sloping and compacting side walls) and lining if necessary with concrete or gabions. The economic practicalities and engineering judgement are difficult to implement owing to the lack of understanding of the factors leading to gully erosion in a changing environment. The officials have questions as to the effectiveness of the current stabilization approaches in preventing future excessive erosion occurrences.

In order to assess the factors behind the excessive gully erosion in the Omaha area a preliminary investigation was initiated to define hydrologic, geotechnical, and hydraulic factors involved in the gullying process. Included in the preliminary investigation was an analysis of a specific watershed situated in a subdivision (Echo Hills) in the southwestern corner of the Omaha Metropolitan area. The Echo Hills subdivision gully was ideal for a detailed analysis for three reasons. First, a severe gully erosion problem exists in this drainage. Second, it was easily accessible for field evaluation. Finally, some preliminary surveying efforts were conducted for the purpose of designing a future channel stabilization project. This was ideal for predicting the hydraulic and geotechnical response of the system to various factors.

The area of the Echo Hills watershed is about 85 hectares. The channel drainage slope averages 1.64 percent with a watershed length of about 2 kilometers. In the natural undeveloped condition the impervious area would constitute approximately 5 percent of the total area. Under current development conditions the impervious area is approximately 24 percent of the total watershed area. When development is completed it is anticipated that the impervious area will be 50 percent of the total area. Using this information and hydrologic routing procedures estimates indicate that peak discharge has increased significantly. For instance, given a 2 year peak discharge associated with a 76 mm rainfall (11.2 mm runoff) the peak discharge was estimated to be 5.4 cubic meter per second versus 10.5 cubic meter per second when comparing pre-urban with the current development conditions. The relative difference is of course more exaggerated for flows of lesser recurrence intervals and not as significant for flows of greater recurrence intervals than 2 years. Further discussion on the hydrological factors are contained in Remus (1985) and Nicklin (1986) for this watershed.

Geotechnical Analysis

In order to make a preliminary assessment of the geotechnical properties of the loessial soil in the Echo Hills subdivision, large block samples were dug from the gully walls. Block samples provide a high quality of undisturbed test samples. The samples were handled in accordance with standard procedures. Each of the blocks was later carved into several individual soil specimens for a series of consolidated undrained triaxial shear tests (both with and without pore pressure). Further, the samples were subjected to crumb tests and liquid and plastic limited determination.

The results compared well with other documented soil property evidence in the general study area (e.g. Benak, 1967).

The crumb test is used to identify dispersive clays (Sherard, 1976). Clays are considered to be dispersive when the interparticle forces are

Table 1. Stability determinations for selected slopes in the Echo Hills ditch using the Culmann method.

Station Number	Bank Height, m	Back Slope	Failure Slope Unsaturated	Failure Slope Saturated	Factor of Safety Unsaturated	Factor of Safety Saturated
1+00R	3.7	58°	36.7	34.3	2.99	0.27
3+00L	4.5	51	33.2	30.8	2.99	0.31
7+00L	6.1	70	42.7	40.3	1.54	0.22
11+00R	4.8	66	41.0	38.5	1.99	0.23
13+99L	4.6	58	36.7	34.3	2.48	0.27
13+00R	3.8	85	50.2	47.8	1.72	0.17

such that a net repulsion between the clay particles exists. Dispersive soils are highly erodible and subject to piping. The dispersive character is judged according to the degree of colloidal suspension. No colloidal reaction is judged a Grade 1 material. Severe colloidal reaction is judged a Grade 4. Grades 2 and 3 define intermediate degrees of reaction.

Block samples obtained in unleached and deoxidized zones indicated a Grade 3 reaction. Block samples obtained in zones with an apparent exposure time of 3 to 5 years yielded a Grade 1 reaction. The Grade 3 reaction of the recently exposed material could indicate a high Susceptibility to erosion and this is evident in the rapid gully wall growth exhibited in this vicinity. Further assessment in this area is needed to be more conclusive, however.

A series of consolidated undrained triaxial shear test (CU), with and without pore pressure measurements, were conducted to determine the soil parameters c, ϕ, and ϕ'. The CU tests were completed using procedure outlined by Bowles (1978). The cohesion value for unsaturated samples was 20900 N per square meter. For the saturated case the value was approximately 150 N per square meter. These values agree well with values published by Benak (1967) and others. Thus the inference by Lohnes and Handy (1968) that cohesion is negligible for saturated loessial seems relevant in the study area. Table 1 provides a summary of the statistics associated with slopes using the two indices of cohesion and the Culmann method. Interestingly enough all slopes indicated stability in the unsaturated case with factors of safety greater than one. In the saturated case, all the slopes showed very low factors of safety and are thus suspected to be of high instability following significant inundation.

The slopes were also analyzed assuming the existence of tension cracks. In the unsaturated case, the factors of safety were reduced further by 10 to 18 percent. In the saturated case there were no significant reductions in an already low factor of safety.

The limited laboratory and slope stability analysis does reflect the importance of the level of saturation on the factor of safety. It is most likely that the freshly exposed gully walls are subjected to unnaturally high moisture loadings during the significant runoff events. Another factor may be additional hydrologic loading from lawn irrigation in the study area. A detailed laboratory investigation on the level of moisture saturation as they effect the strength of loessial soil banks is needed to more accurately define slope failure likelihoods. Work is also needed to determine the seasonal aspects of failure owned to freezing and thawing and other factors.

Analysis of Hydraulic Factors

In an earlier section the effects of urbanization on the watershed hydrology through increased runoff volume and rates were inferred. It is

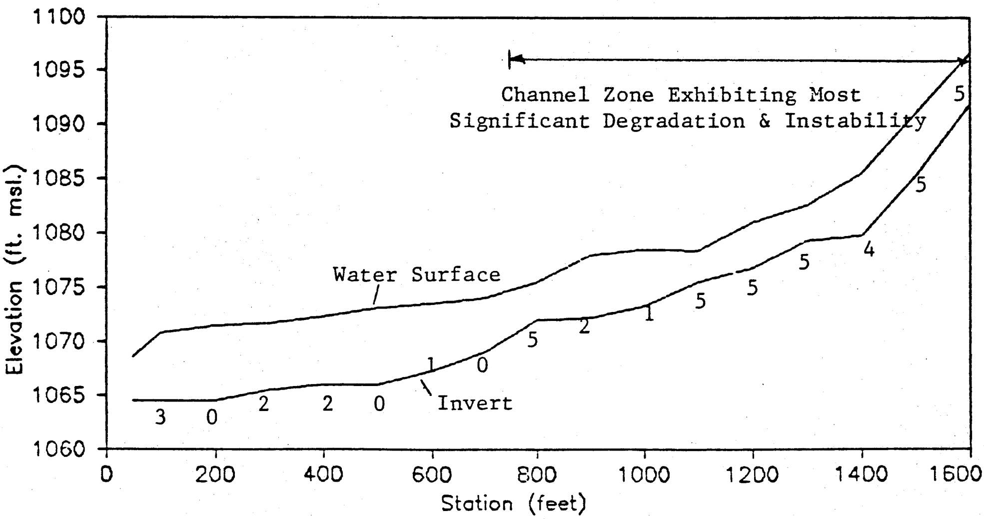


Figure 3. A plot of the channel profile with scour indices. The higher scour indices correspond to higher predicted scour. Generally, the channel zones exhibiting high degradation and instability agree well with the indices.

obvious that any alteration of the system hydrology will also impact the channel system's hydraulics. Although this effect may be substantial for events of all recurrence intervals, it is with the high frequency events where the impacts are most pronounced. It may be recalled that the runoff for a 2 year event under a predevelopment and current development scenario was 5.4 versus 10.5 cms. It is predicted that the 2 year runoff with 50 percent development would be approximately 19 cms. The implications are obvious for this and other watersheds in the vicinity.

Based upon a qualitative interpretation of areal photography, the rate of gullying appears to be approximately constant from year to year. It is speculated this may be in part related to the seasonal geotechnical failure following freezing and thawing and periodic saturation in the major runoff months occurring in early spring. Thus it would be expected that the more frequent events would be responsible for a large fraction of the failed gully wall material from the channel. This explanation seems plausible since the rate of gullying from year to year seems relatively constant despite an assortment of rainfall events occurring over the last 10 years ranging from the more frequent events to one event possibly exceeding the 100 year rainfall.

In an earlier section the significance of the methodology developed by Hughes was implied. Hughes' work which utilized the so-called "asymmetric probability function" where the following relationship applies

$$V = KY^m$$

The coefficients K and m vary according to the type of material. K values are dependent upon the type of material and upon the liklihood of scour. For sandy-silts K varies from 2.12 to 3.44, for silty-clay K varies from 2.00 to 3.89, and for clay K varies from 2.69 to 4.88. For sandy-silt and silty-clay m is 0.2. For clay m = 0.25. Considering that loess soils in the investigation were considered intermediate between the sandy-silt and silty-clay intermediate K values were chosen (e.g. K = 2.06

for a 0.01 liklihood of scour and K = 3.66 for a 0.99 liklihood of scour. Intermediate K values were chosen for intermediate liklihoods for use in the Echo-Hills gully. Some caution may be warranted here as materials with high void ratios may require smaller threshold velocities. This should be considered in further investigation.

The Echo-Hills gully was surveyed in 1983 for potential stabilization work. Mean channel streamflow velocities were estimated from the peak discharges associated with various events along the surveyed sections. The velocities and depths associated with the peak discharges were subsequently plotted on a log-log graph and compared with scour probabilities following Hughes' empirical equation. A typical plot is indicated in Figure 3 for the 2 year runoff under current development conditions. Indices from 0 to 5 were utilized according to the liklihood of scour. The minimum probability of less than 0.01 was defined with an indice of 0. The maximum probability was defined as 5. Intermediate indices were attached to liklihood ranges between the two extremes. The indicies were computed and then compared with stations along the channel. There was general agreement between the severity of the erosion index and the severity of channel degradation problem. For a visual aid the indices are plotted below the channel in Figure 3. The portions of the channel with the highest indices correspond with the gully walls exhibiting most rapid gully erosion through scour removal of geotechnically unstable material. Although the data is somewhat limited and we hope to determine K and m values more specific to the study area with further investigation, the results are encouraging.

SUMMARY AND CONCLUSIONS

Gully erosion is a major problem of concern in loessial soils. The current investigation, although preliminary in nature, has shown that the gully erosion problem is likely related to three interactive factors, including alterations of the hydrologic system, leading to increased hydraulic loadings and more frequent inundation of moisture sensitive loessial soil materials. The Culmann methods indicate that if saturation of loessial soils is a problem that gully banks are highly unstable leading to subsequent failures and subsequent removal by scouring flows.

REFERENCES

ASCE Task Committee. 1968. Erosion of cohesive sediments. Journal of Hydr. Div. ASCE, V. 94, HY4.

Benak, J. V. 1967. Engineering properties of Late Pleistocene loess in the Omaha - Council Bluffs area. Ph.D. Thesis, University of Illinois.

Bradford, J. M. and R. F. Piest. 1976. Gully wall stability in loess-derived alluvium.

Castellano, R. H. 1961. A study in clay mineralogy and the relationship of the clays to soils and texture in selected exposures of the Loveland and Peorian formations in eastern Nebraska and western Iowa. Ph.D. thesis, UNL, Lincoln, NE.

Condra, G. E. and E. C. Reed. 1950. Correlation of the Pleistocene deposits of Nebraska. Conservation and Survey Div. Bulletin 15-A.

Daniels, R. B. and R. L. Handy. 1959. Suggested new type section for the Loveland loess in Western Iowa. Journ. Geol. 67:114-119.

Hughes, W. C. 1980. Scour velocities in ephemeral channels. Journal of Hydr. Div. ASCE, V.106, HY 9.

Lohnes, R. A. and R. L. Handy. 1968. Slope angles in friable loess. Journal of Geology. Vol. 76, p. 247-258.

Partheniades, E. and R. E. Paaswell. 1970. Erodibility of channels with cohesive boundary. Journal of Hdr. Div. ASCE, V. 96, HY3.

Piest, R. F., J. M. Bradford and E. M. Wyatt. 1975. Soil erosion and sediment transport from gullies. Journal of Hydr. Div. ASCE, V. 101, HY1.

Remus, J. I. 1985. Gully and streambank erosion of loessial soil in the Papio Creek Watershed through Omaha. M. S. Thesis. UNL - Nebraska.

Ruhe, R. V., J. G. Cady, and R. B. Daniels. 1966. Landscape evolution and soil formation in southwestern Iowa. USDA Technical Bulletin 1349.

Terzaghi. 1943. Theoretical Soil Mechanics. J. Wiley & Sons.