PIPING AS A MECHANISM OF BANK EROSION
ALONG RIVERS IN IOWA

by

Douglas J. Luzbetak, Subhash C. Jain, and A. Jacob Odgaard

Submitted to
Iowa State Water Resources Research Institute

IIHR Report No. 324
Iowa Institute of Hydraulic Research
The University of Iowa
Iowa City, Iowa 52242-1585 USA
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ACKNOWLEDGEMENTS

The research on which this report is based was financed in part by the United States Department of the Interior, Geological Survey, through the Iowa State Water Resources Research Institute (Project No. G-1225-03). The contents of this publication do not necessarily reflect the views and policies of the U.S. Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement by the United States Government.
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LIST OF SYMBOLS

c = Cohesion of soil

\( d_g \) = Geometric mean diameter

\( D_{50} \) = Arithmetic mean diameter

FS = Factor of safety

h = Height of water in tension crack

\( h_1 \) = Height of water above sand lens on bank face

H = Height of block of cohesive soil

L = Length of sand eroded from the lens

s = Standard deviation

S.G. = Specific gravity

W = Weight of block of cohesive soil

\( W_{50} \) = Mean fall velocity of the particles

\( \delta_w \) = Unit weight of water

\( \sigma \) = Maximum tension stress required for stability against overturning
CHAPTER I

INTRODUCTION

Each year in Iowa, thousands of tons of valuable top soil are lost through erosion into rivers and streams. In a study by Odgaard (1984), it was found that at least forty-six percent of the suspended sediment leaving the state of Iowa through its river systems originates from instream bank erosion. Much of this erosion occurs along alluvial streambanks, and this erosion is quickly gaining importance and visibility as both an economic and mechanics problem. There are many different opinions about the mechanisms by which streambanks fail, but there are only a few detailed studies of bank erosion. In order to rationally develop and implement an effective streambank protection program, it is necessary to fully understand the processes responsible for changes in river geometry and bank erosion.

Changes in river geometry rely on a variety of forces and combinations thereof. In a study of riverbank stability by Springer (1984), four major forces that may cause these changes are noted. These are the erosive actions of water flow, wind and boat waves, seepage forces produced by the
movement of groundwater, and ice. Increases in these forces combine with circumstances which reduce the resistance of the bank material, leading to a lessening of the overall stability of a bank and eventually to failure.

The process of bank erosion is very complicated. In a study describing bank failures by Thorne (1978), the mechanics of bank failures are related not only to the nature of the forces acting on the bank, but also to the size, geometry, and structure of the bank itself, and to the properties of bank materials. These factors act in various combinations to affect the stability of the bank and therefore the erosion processes that occur.

Banks are generally believed to fail by corrosion or structural failure of the soil or a combination of both. In the bank erosion mechanism suggested by Turnbull et al. (1966), the river erodes by corroding a deep pool at the toe of the bank, which steepens the bank, makes the slope unstable, and, eventually, gives rise to a structural failure of subaqueous and upper banks. This mechanism is widely accepted and suggests that basal scour is the prime cause of for bank erosion, and it leads to the notion that bank erosion is a local phenomenon which is confined to meander bends and artificial structures where basal scour is promoted. However, it seems unlikely that local erosion of river banks can produce such large sediment contributions to
streams as indicated by the study cited above (Odgaard 1984) unless there are other mechanisms of bank erosion for which basal scour is not a prerequisite. Recent studies (Thorne 1978; Hooke 1979; McLane 1984; Hagerty 1984a, 1984b, 1984c; Springer et al. 1985) indicate that the erosion of bank soils by groundwater flowing out of the bank face may be a major factor in subsequent bank failure and erosion.

There have been many studies contributing to the present belief that undercutting of a bank by erosion of a layer plays a major role in bank instability. Piping occurs when a sand lens is eroded due to water seeping out of it. Kenney and Lau (1985) and Goss (1973) investigated the influence of the grain sizes encountered in lenses on the probability of piping occurring. In his study on seepage accompanying drawdown events, Desai (1972) discusses the differences in seepage rates out of different sections and layers of a bank with different permeabilities. He also suggests that different seepage forces, resulting from these different seepage rates, may affect bank stability. Burghi and Karaki (1971) also studied seepage effects on channel bank stability and found that an increase in area of side slope erosion with the addition of groundwater was directly related to the average hydraulic gradient and the flow velocity in the channel. Some authors feel that the drawdown surface slope plays a role in bank stability due to
seepage, and Newlin and Rossier (1967) and Desai and Sherman (1971) have investigated the effects of drawdown on the free-surface flow emerging from a bank. Clifton et al. (1971) also noted that the discharge of an aquifer is one factor affecting slope stability.

There have been several studies that confirm some of the problems piping causes in slope stability. Parker and Jenne (1967) investigated piping along highways and railroad beds in the western United States. They found that piping is very common and causes a great deal of problems resulting from its effect on slope failure. Brown (1962) investigated several areas where erosion was caused solely by piping in Colorado. Hagerty (1984a, 1984b, 1984c) has documented many cases of failure in alluvial banks in the Ohio River basin that have been obviously caused by piping.

The studies above have all contributed to the widely held belief that piping is a widespread, though not well understood, phenomena. They also confirm that piping occurs in banks with similar characteristics as those found in Iowa. These studies, although really not studying the piping problem as a whole, do provide useful analysis in investigating piping as a factor in bank instability.
CHAPTER II
FIELD DATA AND OBSERVATIONS

The objective of the collection of field data was to see if there were any obvious differences between alluvial banks that were actively eroding in the straight sections and bends and those appearing to only be actively eroding in the bends. Samples were obtained from two different locations in east-central Iowa which appeared to be representative of alluvial streambanks found in this area. One site was on the Cedar River near Rochester, Iowa, where samples were taken at several locations. The other site was on the English River near Wellman, Iowa. The differences between these two sites was that it appeared erosion was actively occurring both in the straight sections and in the bends on the Cedar River whereas on the English River erosion appeared only to be actively occurring in the bends. Another difference was that sand lenses were visible at many locations on the Cedar River (see figure 1) while the banks of the English River appeared to consist of a uniform, cohesive material.

Potential sampling sites were located by visual inspection from a boat in the Cedar River and from the banks
Figure 1. Sand lens in cohesive river bank. Cedar River, Iowa.
on the English River. If a site looked promising, a closer, more thorough inspection was then performed. First, a vertical cut was made in the bank to remove material which may have been deposited and expose the soil layers underneath. These cuts were extended as far back from the face of the bank as feasible so the presence of distinct layers could be confirmed to extend back into the bank and to discount the possibility that localized deposits were sampled. Then, if the existence of these layers was confirmed, samples of the bank material were taken at various locations along the bank.

The banks which were sampled were approximately ten to fifteen feet high and relatively steep (about 70 degrees from the horizontal). At one straight section on the Cedar River, it was apparent that some rip-rap had at one time been placed on the bank to protect it from erosion and was now laying at the base of the bank several feet from the bank face. It was felt that the rip-rap's inability to protect the bank at this point was due to the fact that the bank failures at this section were caused by piping. Three visits were made to the Cedar River, two in early June and one in late October in 1987. During the fall visit the water levels were much lower and a terraced bank form, much like that described by Springer (1984) occurring on the Ohio River and its tributaries, could be observed more clearly.
along the river (see figure 2).

A size analysis was run on each sample using standardized sieve and hydrometer methods and were classified according to the M.I.T. grain size scale (Spangler and Handy 1982). The samples taken from the sand lenses were all distributed in the sand range (10.0 mm-0.06 mm) with the median size of each sample falling within the medium size sand category (0.6 mm-0.2 mm). The samples taken from the other locations on the banks, which appeared to consist of cohesive materials, show a range of smaller sizes. These were distributed mainly in the size range of silt (0.06 mm-0.001 mm), with the median sizes falling within the coarse to medium silt range (0.06 mm-0.006 mm). These results were much as expected and matched predictions based on soil layer distributions presented by Springer (1984) for alluvial river banks in which a bank is represented as being constructed of a series of alternating soil layers due to the deposition by annual floods of layers of clay and silt along with lenses of sand and silty sand. These results also confirmed the belief that, along many alluvial streams in Iowa, the banks are composed of distinct layers whose median sizes differ by a noticeable amount. As a result, these two groups of samples definitely have different hydraulic, structural, and strength characteristics which could lead to large differences in
Figure 2. Terraced alluvial bank showing evidence of piping failures. Cedar River, Iowa.
strength and stability within sections of banks and prove to be a major factor in many bank failures.
CHAPTER III
MODEL DEVELOPMENT

Our model was developed from the bank failure model proposed by Ullrich et al. (1986). This model was developed as a result of a comprehensive study of the stability of alluvial stream banks in the Ohio River system. The model was developed from a range of conditions the authors encountered on alluvial banks, and was based on a refinement of a simple sliding wedge model presented by Springer (1984). In order to observe the basic principles of our model it is first necessary to show how the aforementioned models were developed.

Springer's model examines the sliding stability of a mass of cohesive soil on a layer of sand. It is based on the wedge stability analysis, common in soil mechanics, which was chosen due to the fact that the kinematics of a wedge analysis appear to agree well with the mechanism of failure of many banks he observed in the field. He also chose this method for three additional reasons:

1. It takes the failure surface to be a plane (as he observed at failed banks).
2. The factor of safety is derived from a summation of forces in the horizontal direction. He reasoned that this closely describes the kinematics of actual bank failures.

3. This method can easily be adapted to a computer program.

In his analysis, the sand layer is assumed to be the failure surface on which a cohesive bank slides. An example diagram of this model and its parameters are shown in figure 3.

In this model it is assumed that the failure process is initiated when water flow is at a high stage and the sand lens is submerged. At this time, water flows from the adjacent stream into the sand lens. It is assumed that water flows into the entire thickness of the sand lens, and exerts an uplift pressure on the soil wedge. This pressure can then be analyzed by using a simple force balance to see if sliding occurs. A stability analysis was then run calculating factors of safety while varying the following parameters: bank height, coefficient of permeability of the sand, height of capillary rise in the sand lens, angle of internal friction of the sand, specific weight of the cohesive soil, slope of the sand lens, slope of the top of the bank, maximum river stage, time of rise and fall of the water stage, and tension crack formation. The assumptions regarding tension cracks, if they occurred and if they were
Figure 3. Idealized model of an alluvial riverbank undergoing wedge failure. From Springer (1984).
hydraulically connected with the sand lens, played the most important role in the force balance according to his factor of safety calculations.

Although Springer's (1984) method was based upon mechanics of failure observed in the field, there were considered to be three main weaknesses encountered in the analysis. The first was that this method only considered water entering the lens from the adjacent stream during times of high water; ignoring the fact that water might be flowing out of the sand lens due to a high groundwater table located inland away from the bank. The second weakness was that the method did not consider the possibility of sandy materials below the cohesive zones being removed by internal erosion, as might occur if high rates of seepage were emerging from the lens. If material was removed it would have a pronounced effect on the stability of a wedge. The last weakness was that the wedge analysis did not explain the occurrence of delayed failures, as failures in banks such as those studied by Springer have been known to fail sometimes several months after a flood event (Ullrich et al. 1986).

The analysis presented by Ullrich et al. (1986) extends the wedge failure analysis to consider how stream bank stability is affected by material removal from sand lenses by seeping groundwater. This model arose from the authors'
observations of numerous areas of bank failure in the Ohio River basin, where the characteristics of these failure zones indicated that groundwater flowing out of sandy layers in the banks is a major factor promoting instability. It was not their intent to develop and run a complicated analysis, and therefore many simplifying assumptions were used. Their three major assumptions were:

1. The hydraulic gradient remains linear as water flows into the sand seam during a rise in stream stage.
2. The material is removed from the sandy seam at the same rate that water flows out of it.
3. As the stream bank is undermined by material removed from a sand seam, no creep occurs in the overhanging cohesive materials prior to shearing failure.

In their analysis it is assumed sand is removed from the lens due to piping, and this removal produces stresses in the overlying cohesive materials in the bank that may exceed the internal cohesive strength of the material, at which time failure will occur. A sample diagram of this model and some of its parameters are shown in figure 4.

After this basic model was developed, three separate modes of failure were identified; shearing, overturning, and tension. The mode of tension failure they deemed negligible and did not consider due to its rare occurrence as a failure
Figure 4. Idealized model of an alluvial riverbank undergoing failure caused by piping.

a) Shear failure
b) Overturning failure
mode at field sites. Then, for the other two modes, equations were developed to calculate the factor of safety for failure by each method. The factor of safety equations are:

Shear failure: \( FS = \frac{cH}{W} \)

Overturning failure: \( FS = \frac{2}{3} \times \frac{cH^2}{WL} \)

These equations were developed as a result of a force balance for each mode.

Preliminary calculations were performed using these equations for the soil sample used in the experiments (for a description of some of this samples physical characteristics, as well as those of other materials used in these experiments, see Appendix A). The results show that the model riverbank should fail by overturning; as the factor of safety number for failure by this mode was always less than that calculated for failure by shear. The experiments backed this fact up, as overturning failures were observed on all the runs. This was most likely due to the high cohesive strength of the soil (6.69 lbs/in\(^2\)). Sample calculations of these factor of safety numbers are shown in Appendix B. The lengths of washout at which failure occurred during model tests for this study were less than those predicted using the factor of safety equations. These idealized failure lengths were predicted by setting the factor of safety equal to one and solving for washout
length. Therefore, due to this discrepancy, these equations may need to be refined if they are to be valuable in an analysis.

Ullrich et al. (1986), ran a factor of safety analysis while varying the following parameters: coefficient of permeability, angle of internal friction in the sand lens, cohesion of the bank soil, unit weight of the bank soil, inclination of the sand lens, top slope of the bank, height of the bank above the sand lens, and hydrograph variations common to the Ohio River basin. Values of factor of safety calculated were then compared to see if the stability of the bank (according to this method) was more sensitive to some factors then to others. From their results, they concluded that bank stability is most affected by the coefficient of permeability of the sand lens and the height of capillary rise in the lens, and the inclination of the sand lens. These factors had the greatest effect on bank stability because they drastically affected the amount of the sand lens which would be eroded and the distance to which seepage effects would occur.

It was felt that Ullrich's et al. (1986) method, although based on observed field conditions, is weak in some respects. The method involves the assumption that the sand layers were inclined in the bank, and this parameter turned out to be a very important one in the stability analysis.
Field observations in Iowa showed sand lenses along alluvial streams were effectively horizontal and therefore would have no effect on piping. Another weakness is that the authors assumed the sand lenses were 'charged' only during high-water events; thereby ignoring the possibility of the effects of groundwater flow through a sand lens. A last major weakness is in their handling of vertical tension cracks in the bank. Although the authors recognize that tension cracks exist and that they do play an important role in bank instability, it was felt that a more complete model would have to consider the effects of tension cracks more thoroughly.

In the model developed for this project, the sand lenses are assumed horizontal and it is assumed that groundwater flowing out of the lens has a greater effect than that caused by high water events recharging the lens. The original goal of this study was to find some threshold seepage velocity at which sand would begin to be removed from the lens along with the water flowing out of it. It was desired to find, through experiments with laboratory model of a riverbank, a critical head-seepage rate-erosion rate relationship that could be applied to various general cases. During the experimental trials two important phenomena were observed:
1. Tension cracks play a very important role in the instability of stream banks.

2. Piping appears to be an instability process.

These two observations are discussed further in chapter V.
CHAPTER IV
LABORATORY MODELS

In order to better study the piping mechanism, two physical models were constructed. One was a two-foot-wide by four-foot-high by eight-foot-long watertight box containing a model 'riverbank' (see figure 5). One side of the box consists of a sheet of plexiglass to allow for the viewing of the erosive process, and piezometer taps have been installed on both sides of the model at six inch intervals to enable pressure variations within the sand lens to be measured. The model is also equipped with a variable-height drain to allow stage variations to be run. In this model a 'riverbank' was constructed consisting of a two inch layer of sand contained in a mass of cohesive soil. Varying heads were then run with this model to observe the effects they had on the stability of the sand lens, the water discharged from the sand lens, and the stability of the model bank as a whole. The second model consists of a four-inch-wide by twelve-inch-high by seventy-three-inch-long flume (see figure 6). In this model, sand lenses could also be constructed and the erosion process viewed on a much smaller scale. This models' walls were also constructed of
Figure 5. Large laboratory model containing model riverbank and sand lens.
Figure 6. Small laboratory model showing two different attempts to represent a sand lens.
plexiglass to aid viewing the process, and was also equipped with variable-height drains so that head variations could be run. In this model, a thin layer of sand contained between impervious barriers was run to test the effects of hydraulic gradient on the stability of the sand lens.

Several problems were encountered while using both models. The problems of the small model are be discussed first. The main problem in the small model was undoubtedly the large effects that boundary conditions had on the tests. The small width of the flume restricted us to very narrow test lenses and, as a result, the effects of the sand-wall interaction could be easily transferred throughout the lense. Another source of boundary effects occurred as a result of the top boundary of the lens. The lens was originally topped with a sealed plexiglass piece that formed an impervious barrier to ensure that if water was to be discharged from the head tank behind the lens it would have to pass through the sand lens and not around it. The smoothness of the plexiglass was noticed to be a problem, so other top barriers were tried. A large weight was placed on top of the barrier to enhance the barrier-sand interaction. This method had no positive effects. The sand lens was also topped with a cohesive, impervious, clayey soil. This served the same purpose as the plexiglass cover with the added feature of increased friction at the barrier-sand
interface and an increased weight force on the lens. Again, this alteration showed no positive results. Another method that was tried was placing a vertical barrier at the downstream end a distance away from the head tank and filling the gap between the tank and the barrier with sand (see figure 6). A small opening was left between the barrier and the flume bottom to represent the face of a sand lens. This set-up was virtually useless due to the fact that the sand within the barriers 'arched'; therefore, as soon as any sand was removed from the lens the sand above it did not come down to take its place as had been originally hoped for and a non-homogeneous condition was formed in the lens. This led to a rapid failure condition. The alternative top barriers ultimately were no more successful for eliminating the boundary effects than the plexiglass barrier due to the small width of the flume. Other problems were encountered with these two alternative barriers as, especially with the sand barrier, alternate pathways for the water to follow between the head tank and the lens face were created.

Another limiting factor with the small model was that the head that could be developed behind the lens was restricted to a small amount, about ten inches or less. This limited the model in two ways. First of all, as the head height was limited the length of sand lenses which
could be run with this model also had to be limited. Second, the lens thicknesses that could be attempted were limited also due to the restricted head that could be developed. These two limiting factors combined with the various other effects to create many problems in this model.

The two factors above combined to make observation of the erosion process virtually impossible, as there was usually no erosion process so to speak of during the runs. Instead a sudden, complete washout of the lens would occur. The observations and results from this model will be discussed in greater detail in the laboratory results section.

Many problems were encountered during runs of the large model as well. Again, the major drawbacks were caused by boundary effects. Originally, the sand along the walls was easily washed out due to the lack of friction between the sand and the walls. This was overcome by lining the walls with a wire mesh, which increased the friction force at the sand-wall interaction and helped to hold the sand lens in place. Another problem encountered was due to the arching of the soil. The soil used in this model had a high percentage of clay and a high cohesive strength. Therefore, when a small amount of sand was eroded, the soil maintained its form due to arching effects rather than slumping down to fill the void vacated by the eroded sand. This led to the
situation where a local weakness might be encountered at a spot in the sand lens, which would lead to localized erosion at this spot. This process is called backward erosion (Terzaghi and Peck 1967). Once this localized erosion began, it continued back towards the head tank, and a stable channel would begin forming. Since the soil tended to arch, this channel would remain and would pass a large volume of water through it, leading to the depletion of the water level in the head tank, the rapid removal of a great deal of the sand in the lens, and the ultimate failure of the bank.

Originally the tests in the large model were designed to closely resemble field conditions. These conditions were represented by constructing a thin horizontal sand lens in a mass of cohesive soil. This soil was felt to resemble natural conditions as it was taken from a site along a river and it appeared to be a representative soil of that found elsewhere. The model bank was constructed as follows. First, a six inch deep base of the soil was placed on the bottom of the model. This provided a base for the sand lens to rest upon, and so consequently it was made the same length as the sand lens desired. The soil was applied when it was relatively wet so it would have a chance to settle and form an impervious layer. It was also much easier to handle and shape in this condition. This base was leveled and a layer of sand was then placed on it (see figure 7).
Figure 7. Prepared sand lens for large model. Front view.
Then, on top of the sand, more soil was placed at various slope angles to add a weight force on the sand and also to create an impervious barrier in front of the head tank (see figure 8).

Several problems were encountered in trying to maintain these conditions. One was the ever-present effect of boundary conditions, as these had an adverse effect on our thin lenses. Another was that the soil had to be kept submerged when tests were not being run to avoid possible problems created by the drying and cracking of the clay soil. This drying and cracking proved to be a major problem if left to occur because the cracks in the clay would give the water another route to exit the head tank besides through the sand lens and lead to difficulties. The observations and results from this model will also be discussed in greater detail in the laboratory results section.

These tests were designed to enable the relationship between head-seepage rate-erosion rate for a hypothetical riverbank. Problems were encountered with both models when attempting to take these measurements. The erosion rate could not be measured in either model, as, in the small model, erosion occurred too suddenly. In the large model the eroded particles were widely dispersed in the model and were unable to be recovered. It was also difficult to keep
the soil and sand lens distinctly separated at the face of the bank in the large model. As a result, the desired relationships could not be arrived at.
CHAPTER V
LABORATORY RESULTS

The results from the many runs of these two models were not as hoped. The gradient-seepage rate-erosion rate relationship desired was never attained, due mainly to the numerous problems encountered during the runs as discussed previously. However, although the runs did not produce the desired results, they can still be analyzed and used to note some interesting developments, as discussed below.

During the runs with the large model, the overturning mode of failure as described by Ullrich et al. (1986) was observed to occur several times. This failure occurred at gradients ranging from 0.56 to 0.85, with the median gradient of the runs equalling 0.70. To see an abbreviated version of this process, see figures 8-14. This mode was initiated when a small amount of sand was eroded from the lens. This erosion would lessen the support under the specific section of the bank, leading to an increase of internal shear stresses in the bank and a weakening of the bank. As more sand was eroded and the bank weakened further, tension cracks could be observed forming. These cracks formed when a section of the bank had its base, the
Figure 8. Sand lens contained in cohesive soil, large model, before wetting.
Figure 9. Sand lens contained in cohesive soil, large model. Wetting begun at low head.
Figure 10. Sand lens contained in cohesive soil, large model, head at level nearly high enough to cause failure.
Figure 11. Sand lens contained in cohesive soil, large model, shortly after failure and washout of lens.
Figure 12. Sand lens after failure, with cohesive soil removed, showing erosion.
Figure 13. Sand lens after failure, with cohesive soil removed, showing erosion.
Figure 14. Sand lens after failure, with cohesive soil removed, showing erosion.
sand lens, washed out or partially washed out and its internal cohesive forces could no longer overcome the increasing internal shear stresses. These tension cracks continued to grow downward until they reached the sand lens. At this point they were hydraulically connected to the head tank through the sand lens, and water would fill the tension cracks up to the level of the head tank. This water then exerted pressure on the bank, thereby causing the tension cracks to expand and eventually leading to the failure of the bank.

During the runs involving the small model, a very interesting failure method was noted. The erosion that occurred in this model was very sudden. The lens would appear to remain stable at all heads until a certain critical gradient was reached. Then at this head, the lens would fail en masse and seemingly wash out as a whole. This was felt to be a direct result of the fact that a limited head could only be run, resulting in a small model lens. Since the lens was so small, the sand may have acted as a homogeneous mass or a 'plug'. As hydrostatic pressure was being built up in the head tank behind the lens, no particles were dislodged because the flow rate through the sand was too weak to cause the erosion of any individual particles. Then, as the water level in the head tank continued to rise, the hydrostatic pressure force on the
lens became larger than the restraining friction force between the sand and the barriers and, with the flow rate too small to dislodge any of the particles, a sudden, total failure occurred. The different methods mentioned previously to try and increase the friction force between the sand and boundaries were tried, but with little success.

As discussed earlier, it is felt that two important phenomena were observed during the trials. These will be discussed here. The first was that tension cracks appear to play a very important role in the stability of cohesive banks. The fact that these cracks do have an effect on bank erosion has been mentioned in the literature (Ullrich et al. 1985, Springer 1984) and roughly analyzed, but it is felt a more detailed study is needed regarding the formation of tension cracks and their effects on bank stability. Tension crack formation appears to effect bank instability in two ways. The first is that a tension crack may partially fill with water even during a relatively small rainfall event, and may totally fill during a large event. This water in turn will apply pressure on the soil 'wedge' in front of it, decreasing the stability of the soil and possibly leading to failure. The second effect tension cracks may have is that they may aid in the erosion of the sand lenses. If the cracks are deep enough they may be hydraulically connected with a sand lens. If this is the case, any rainfall or
overland flow the tension cracks may intercept will quickly and almost directly flow into the sand lens. This increase in water reaching the sand lens may aid in the weakening and erosion of the sand lenses, and subsequently lead to bank failure. For these two reasons it is felt that tension crack formation and interaction play a prominent, and largely undefined, role in the erosion of streambanks.

The other phenomenon which is felt to be important is that, in some cases, piping may be an instability problem. Piping has been observed in cases where it has been reported that sand 'virtually flowed' from the banks (Ullrich et al. 1986), and has proved to be a major factor in bank failure through site observations. The main problem is that the mechanism by which piping occurs and influences bank failure is little understood. There are many theories on the causes and effects of piping and the basic mechanisms by which piping occurs are basically agreed upon, but the exact mechanisms and their effects on bank stability as of yet remain uncovered.

Describing piping as an instability problem is a practical assumption, although this process is then difficult to analyze theoretically or analytically. Piping may be described as an instability process due to the following. Once piping begins, it becomes an accelerating process. This is because as the first sand is removed, the
length of the lens is decreased slightly, and therefore the hydraulic gradient is increased (assuming the head remains constant). Then, because the hydraulic gradient is increased, erosion is increased, the length of the lens is shortened, and the whole process is started over again. Although under conditions similar to those found in nature this process would still occur as described, the acceleration of the process would presumably be very slow, and it is doubtful whether it would have an effect at all. However, if certain conditions were present, such as a sudden, very large increase in head or some irregularity in a lens that causes it to act greatly shortened such as a tension crack which is suddenly intercepting a great deal of overland flow and delivering it to the lens, this acceleration of the piping process could be very rapid. This accelerating process was noted during the runs of the lab models. Under lab conditions with relatively thin and short lenses, this process accelerates very quickly and creates difficulty in establishing relatively constant conditions to enable measurements to be taken. In retrospect, many of the problems discussed above may have been perceived as problems due to a lack of understanding of the possibility that instability may have played a role and triggered the "undesirable" channelization or washout of sand. Most of our tests were attempts to establish a
steady-state condition in which the correlation between head, seepage rate, and erosion rate could be measured. Now, the indications are that a steady-state situation is unobtainable even in the field.
CHAPTER VI
CONCLUSIONS

Three important phenomena were brought to light by the present study, and it is important that each receive further study. The first is that of tension crack formation and propagation. Tension cracks seem to play a very important role in the problem of bank instability and, in some cases, it appears that tension cracks are a major factor in bank erosion. Improved understanding of the behavior of tension cracks is imperative to the understanding of the process of bank erosion due to piping. Another observation is that piping is an instability problem. This process may prove to be important regarding why piping erosion occurs in some areas and not in others. A final observation is that the grading of the sand lens may have a large effect on the resistance of the lens to internal erosion and therefore subsequent bank failures. Studies have been performed dealing with the effects that grading has on filter stability (Kenney and Lau 1985), and these tests could be extended or modified in some way to apply to sand lenses.

It is felt that the above observations must be more fully investigated and understood before the occurrence of
Bank failures due to piping can be effectively remedied. There are many modes of possible solutions, such as the installation of filters or horizontal drains. It is obvious that, although piping is a recognized and often identified mechanism involved in bank erosion along rivers in Iowa, there is much room for further research to aid the understanding and possible remedies of this problem.
REFERENCES


APPENDIX A

SOIL/SAND CHARACTERISTICS

Soil Data

Cohesion (c) = 6.69 lbs/ft$^2$

Specific gravity = 2.70

Size distribution: 36.4% sand
12.4% silt
51.2% clay

Liquid limit: 42%
Plasticity limit: 17.3%
Plasticity index: 12%

Sand #1

$d_g$ = 0.277 mm
$D_{50}$ = 0.295 mm
$s$ = 1.52
$W_{50}$ = 42.4 mm/s
S.G. = 2.67

Sand #2

$d_g$ = 0.269 mm
$D_{50}$ = 0.289 mm
$s$ = 1.35
$W_{50}$ = 41.1 mm/s
S.G. = 2.65
APPENDIX B

FACTOR OF SAFETY EQUATIONS

Shear FS: \( \frac{cH}{W} \)

Overturning FS: \( \frac{(2/3)(cH^2/WL)}{\text{WL}} \)

These equations were derived using a simple force balance. The factor of safety against shear failure is simply the shear resistance divided by the weight of the overhanging block per unit length of block (see figure 4). For the overhanging mode of failure a hinge point was assumed at the lower end of the potential failure plane. The factor of safety for this mode was then determined by dividing the cohesion of the materials by the maximum tension stress developed in the bank materials. The slope angle of the face of the model bank was usually near 45°, therefore in these calculations, it was assumed \( L=H \).

S.G. = 2.70

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