BANK PROCESSES ON THE RED RIVER BETWEEN
INDEX, ARKANSAS AND SHREVEPORT, LOUISIANA

Final Technical Report

By

Colin R. Thorne

May 1989

United States Army

EUROPEAN RESEARCH OFFICE OF THE U.S. ARMY

London England

Contract Number DAJ45-88-C-0018

Queen Mary College, University of London, UK

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

ABSTRACT

The Corps of Engineers is currently constructing a multi-million dollar scheme to make the Lower Red River navigable. Concerns have been expressed regarding sedimentation problems in the navigation reach caused by the heavy sediment input from upstream. It is believed that bank erosion in the reach between Index, Arkansas and Shreveport, Louisiana is a major source of this sediment.

Studies of bank and bend processes were undertaken on the Red River between Index, Arkansas and Shreveport, Louisiana. The aims were to determine: the nature of the bank materials and the dominant mechanisms of bank failure; the role of outer bank type in affecting the scour depth of meander bends; and the possible impact of bank stabilization schemes on scour depth.

The results show that the banks are formed in materials of four different origins: meander belt alluvium and clay plug materials associated with the present flood plain; back swamp deposits in a terrace left from the nineteenth century flood plain; and Pleistocene/Tertiary materials in the valley walls. Slab failures and rotational slips are the dominant failure modes. The Osman-Thorne analyses of bank stability were found to be useful in predicting the critical geometry for failure of banks formed in the different materials.

A relationship between outer bank type and bend scour depth was found. Generally, scour depth increases as outer bank resistance to erosion and failure increases, especially for tight bends of low radius of curvature to width ratio. Maximum scour pool depths for revetted bends are 5 to 20% greater than those in the equivalent free, alluvial meander.

These results suggest that some additional bed scour should be expected as a consequence of stabilizing the remaining free meanders in the study reach, promoting delta type deposition at the head of pools in the navigation reach, but reducing sedimentation in the lock chambers and behind the dams.

KEYWORDS

Alluvial river	Bend scour	Meander bend geometry
Meandering	Navigation	Red River
Riverbank erosion	Riverbank material	Sedimentation

I INTRODUCTION

This study is concerned with a reach of the Red River extending from Index, Arkansas to Shreveport, Louisiana (Fig. 1). This reach of river has undergone intense morphological change during the last 100 years. Prior to that time, the river below Shreveport was heavily blocked by a massive accumulation of timber called the Great Red River Raft. At the time of its removal the raft occupied the channel from near the Arkansas-Louisiana state line to a point some 160 miles downstream. It reduced flow velocities and raised flowlines in the river so much that a multi-channel or anastomosing pattern resulted from the frequent overbank events. The raft was removed under the direction of Captain Shreve, the work being essentially completed by 1873, although new jams formed and were removed for another 25 years. A recent review of the raft and its removal may be found in McCall, 1988. The removal of the raft allowed the river to form a single channel and concentration of the stream's energy led to approximately 15 feet of bed degradation in the vicinity of Shreveport (Veatch, 1906). Degradation became progressively less severe going upstream, the bed lowering being about 5 feet at Index. Response of the channel width to lowering of the bed was also spectacular. Prior to raft removal the channel width was of the order of 350 feet. This increased to over 1000 feet. Channel sinuosity decreased following raft removal, from about 2.3 in 1886, to about 1.5 in 1968. Since 1968 a program of channel re-alignments undertaken by the Corps of Engineers has further reduced sinuosity to about 1.36.

A comprehensive study of the geomorphology of the Red River from Denison Dam to Shreveport was recently performed by Water Engineering and Technology Inc., for the Vicksburg District, US Army Corps of Engineers. The reader interested in learning more about the recent history of the Index-Shreveport reach is referred to their 226 page report on this topic (WET, 1987a).

One of the main conclusions of the WET report is that response of the channel in the study reach to raft removal is essentially complete and that the channel is now in a state of dynamic equilibrium. That is, the average depth, width and slope of the channel are time invariant, although channel migration continues. This is possible because erosion of the outer banks in bendways is just balanced by inner bank deposition, so that the channel sweeps back and forth across its meander belt without a significant change in overall cross-sectional size. Also, in a dynamically stable river, reductions in sinuosity through natural cut-offs of meanders are just balanced by the growth of other meanders, so that the overall sinuosity of the reach is steady. This is not the case on the Red, however, because several cut-offs have been initiated artificially, leading to reduction of sinuosity which is on-going.

Even so, it must be concluded that, at least in comparison to the previous 80 years, the Red River has been dynamically stable during the last decade.

However, the present configuration of the channel, and particularly the nature of the stream banks, are direct results of the recent history of channel instability. Hence, in order to explain contemporary processes and mechanisms responsible for bank retreat, it is necessary to understand why the geometry and geotechnical properties of the banks vary along the study reach. These topics are addressed in Section 3.1, on riverbank studies.

In section 3.2, the link between bank processes and bed scour in bends is examined. It is shown that these two directions of channel boundary deformation in bends are closely related and that attempts to control bank erosion will almost always impact bed scouring.

Section 3 uses the implications of Sections 1 and 2 to predict the likely channel response to further bank stabilization schemes.

Finally, Section 4 reports briefly on assimilation of data from a channel re-alignment, which might be useful in further numerical work on bed and bank process inter-actions.

II STATEMENT OF PROBLEM

The US Army Corps of Engineers is currently undertaking a multi-million dollar project to make the Red River navigable up to Shreveport. This involves construction of 5 locks and dams to provide a 9 ft navigation channel. Because they lower the water surface gradient, the dams tend to induce deposition of sediment carried by the flow, and this sometimes requires dredging to maintain the navigation channel. As the sediment load of the Red River at Shreveport is high, it is anticipated that the dredging requirement may be considerable when all the locks and dams are in place in the mid 1990's. For comparison, some serious sediment-related problems have been encountered on the Arkansas River, which for 15 years has had a navigation scheme somewhat similar to that being constructed on the Red. The sediment load concentrations in the Red River are an order of magnitude greater than those on the Arkansas.

2.1 Bank Processes

It is not presently planned to extend navigation upstream of Shreveport into the study reach. But it has been estimated that the sediment yield from bank erosion in the study reach may be of the order of 64 million tons per year (Biedenharn, personal communication, 1988). Although a large percentage of this sediment goes into point and middle bar storage (WET, 1987a), it is logical to conclude that bank erosion is a major source of material in the sediment load at Shreveport. This is also consistent with the observed increase in the annual sediment discharge from 20 to 32 million tons per year between Fulton and Shreveport (Raphelt, 1986). However, it is notoriously difficult to estimate sediment deposition or erosion from the difference between two rating curves (WET, 1987a) and so Raphelt's conclusion should be accepted cautiously.

It is also noteworthy that the grain size of sediment derived from bank erosion is considerably smaller than that derived from bed scour. Material in transport in a river which is finer than that found in the bed is termed "wash load". In a study of wash load in the Red River, Yu and Wolman (1986) found that 90% of this type of sediment came from bank erosion. Recent experience at Lock and Dam 1 on the Red River suggests that it is the finer fraction in the sediment load that poses the most severe problems for efficient operation and maintenance of the navigation project. Consequently, a sound understanding of the processes and mechanisms controlling the bank erosion that inputs this sediment is important when selecting the best approach to controling and reducing the dredging requirement in the navigation reach.

Theoretically, one way to reduce sediment-related problems would be to reduce the sediment load at the head of navigation at Shreveport, by stabilizing the banks in the Index-Shreveport reach. Intuitively, this follows because bank stabilization cuts off the source of the sediment. However, bank stabilization might not lead directly to sediment load reduction, if some side effects cause an increase in sediment supply from sources other than the banks. There are three major impacts of bank stabilization that may promote scour that could off-set the reduction in sediment availability from the banks:

1. Increased bed scour in revetted bends;
2. Reduced sediment storage capacity in crossing bars;
3. Enhanced sediment transport capacity due to channel re-alignment.

Each of these impacts is considered briefly in the following sections.

2.2 Increased Bend Scour in Revetted Bends

As long ago as 1945, Friedkin observed experimentally that stabilization of the eroding outer bank in a free, alluvial meander led to excess scouring of the bed adjacent to that bank. Recently, Thorne and Osman (1988) put forward a theorectical explaination of this phenomenon, on the basis of considerations of bank stability and sediment flux at the toe of the outer bank.

In a migrating bend, erosion of the outer bank and scour at the bank toe keep the bank close to its critical height for mass failure under gravity. This limits the scour pool depth adjacent to the bank, because if the flow attempts to further scour the bed and increase the bank height, bank failures are generated and the rate of bend migration increases instead. In this way the balance of sediment input to the toe area by bank erosion and mass failures is adjusted to satisfy the capacity of the flow in this area to entrain and remove sediment.

When the bank is stabilized with a revetment, bank erosion ceases and gravity induced failures no longer occur. The impact on bed scour adjacent to the toe is two fold. First, stabilization of the bank allows the scour pool depth to increase because toe scour no longer induces gravity failures. Second, the input of sediment from bank erosion and failures is cut-off, so that the bed becomes the only available source of sediment to satisfy the transport capacity of the near bank flow. Consequently, toe scour is promoted and scour pools in revetted bends are expected to be deeper than those in geometrically and hydraulically similar free meanders.

Obviously, this assumes that the increased toe scour has been accounted for in the design of the revetment, to prevent failure by launching.

If one of the main purposes of revetting the banks and stabilizing the meanders is to reduce the sediment load, then the question arises as to whether bank stabilization will simply substitute bed sediments for bank sediments with little short term reduction in sediment production.

2.3 Reduced sediment storage capacity in crossing bars

Often, a series of bends is stabilized by revetting of the outer banks in each bend. Current practice is to continue the revetment well downstream of the bend exit, because experience shows that the point of maximum attack on the outer bank migrates downstream almost to the meander inflection point at times of high in-bank flow. Usually then, the revetment for one bend overlaps with that for the next bend downstream. Under these circumstances, Friedkin's 1945 flume study demonstrated that the capacity of the channel to store sediment in the mid-channel bar located in the crossing between bends is reduced. Consequently, crossing bed elevations are lowered with the benefits of lowered flowlines during floods and increased navigation depths at low flows, but at the cost of the more rapid transmission of sediments downstream through the system. That means that the capacity of the channel to *store* sediment being input from upstream is reduced, so that the sediment *output* downstream may increase.

If the primary aim of revetting bends in the study reach is to reduce the sediment load at Shreveport, then if significant, the effect of reducing crossing storage of sediment would be counter-productive.

2.4 Enhanced sediment transport capacity due to channel re-alignment

Sometimes bends are revetted along their current alignment, but more usually the channel is re-aligned to produce a lower sinuosity and a shorter crossing between bends. This may involve a relatively small reduction in sinuosity, through channel training, or a major reduction in sinuosity, through artificial neck cut-off of an entire meander loop. Re-alignment complicates the relation between bank stabilization and reduced sediment load for two reasons.

First, it increases the channel gradient. Sediment transport capacity is known to be a power function of channel slope. Hence increasing the slope of a channel usually produces a large increase in sediment load, the bed and banks of the channel being eroded to supply the sediment. In the case of the Red River, bank stabilization precludes bank erosion and so bed scour alone would result. This could more than off-set the tendency for a reduction in sediment load due to bank protection , so that the net effect of bank stabilization and channel re-alignment might be an increase in sediment load at Shreveport.

Second, it reduces flow resistance due to channel non-uniformity. Meander bends are known to cause resistance to flow (Bagnold, 1960), and this can be a considerable contribution to overall resistance in tortuous bends. Hence, removing the bends reduces overall flow resistance and increases the flow velocity (and, therefore the sediment transport capacity) even more than would be expected from the increase in channel gradient. When a tortuous channel is straightened, velocity increases of the order of 50% have been observed, 20% being attributed to increased gradient and 30% to reduced flow resistance (Biedenharn, personal communication, 1989).

In fact about 60% of the meander bends in this reach have already been stabilized by revetments, and plans have been approved for most of the remaining free bends to be similarly dealt with. Consequently, it should be possible to investigate some of these effects by examining the response of the river to the engineering works that are already in place.

III TECHNICAL REPORT

3.1 Riverbank Studies

3.1.1 Mechanics of bank retreat

Serious bank retreat usually occurs by a combination of flow erosion of intact bank material and mass failure of the bank due to gravity, followed by basal clean-out of the failed material from the bank toe. The relative importance of these two components of bank retreat depends on the processes responsible for erosion and the geometry, scale and geotechnical properties of the bank. A thorough review of bank erosion processes and mechanisms of failure may be found in Thorne (1982).

Recently, Osman and Thorne (1988) have developed bank stability analyses that can be used to predict the factor of safety of a bank with respect to either slab-type or rotational slip failure. The anlalyses show that the geometry of the bank and the critical mode of failure depends mostly on the geotechnical properties of the bank material.

3.1.2 Red River bank materials

The banks of the Red River in the study reach are formed in a variety of materials that have been broadly classified on the basis of their origin and age as follows:

1. Meander Belt Alluvium (MBA) - material deposited in the present flood plain, under the present flow regime.
2. Clay Plug Deposits (CP) - fine material deposited in cut-off meanders and ox-bow lakes.
3. Back Swamp deposits (BSD) - Sediments laid down in the 19th Century flood plain by over bank flows.
4. Pleistocene Deposits (PI) - Lithified materials in high terraces and the valley sides.

These different materials have quite different engineering and geotechnical properties and, therefore, could have different characteristic bank geometries and modes of failure.

This was investigated by a combination of documentary study, field reconnaissance and theoretical analysis.

The documentary study was based on the 1980/81 hydrographic survey. Cross-sections were selected that included stable and eroding banks from each of the bank material types. The cross-sections were computer plotted and the plots were then used to derive data on the bank heights and angles. These data are shown, by bank type, in Fig. 2 a - d.

Examination of the data in Fig. 2 shows that banks formed in Pleistocene materials (PI) are mostly in the range of 25 to 35 ft high, those in back swamp deposits (BSD) are in the range 20 - 30 ft, clay plugs (CP) 15 - 25 ft and meander belt alluvium (MBA), 10 - 30 ft high. The terrace banks (Pleistocene and back swamps) should be higher than those formed by contemporary fluvial processes (clay plugs and meander belt alluvium), given the origin of the bank types and the degradational history of the river over the last 100 years. Hence, these results are just as expected.

Two limitations should be noted concerning the data in Fig. 2. First, it is very difficult to survey high banks with angles steeper than can be walked or scrambled down. Hence, there is a tendency for field crews to avoid the steepest bank sections. Consequently, there is a tendency for bank geometry data derived from hydrographic survey results to omit the steepest sections. Where such sections cannot be avoided, one sighting is taken at the top of tne bank and another at the base, with no intervening points on the steep, inaccessible bank face. This technique tends to produce underestimates of the true bank angle. The outcome is that the distribution of bank heights is truncated at about 45^{o} - which is the steepest bank that can be walked/scrambled down without serious difficulty. This effect has been noted by other researchers (WET, 1987b) and in other creeks (Thorne, 1988).

Truncation of the bank angle distributions is evident in Fig. 2. There are very few banks steeper than about 45^{o}. This does not mean that steep banks are not found in the field, they certainly are. It is a limitation of the data. Field reconnaissance revealed that many eroding banks have angles in the range 60^{o} to 75^{o}, although lack of time prevented the time consuming measurement of bank angles in the field.

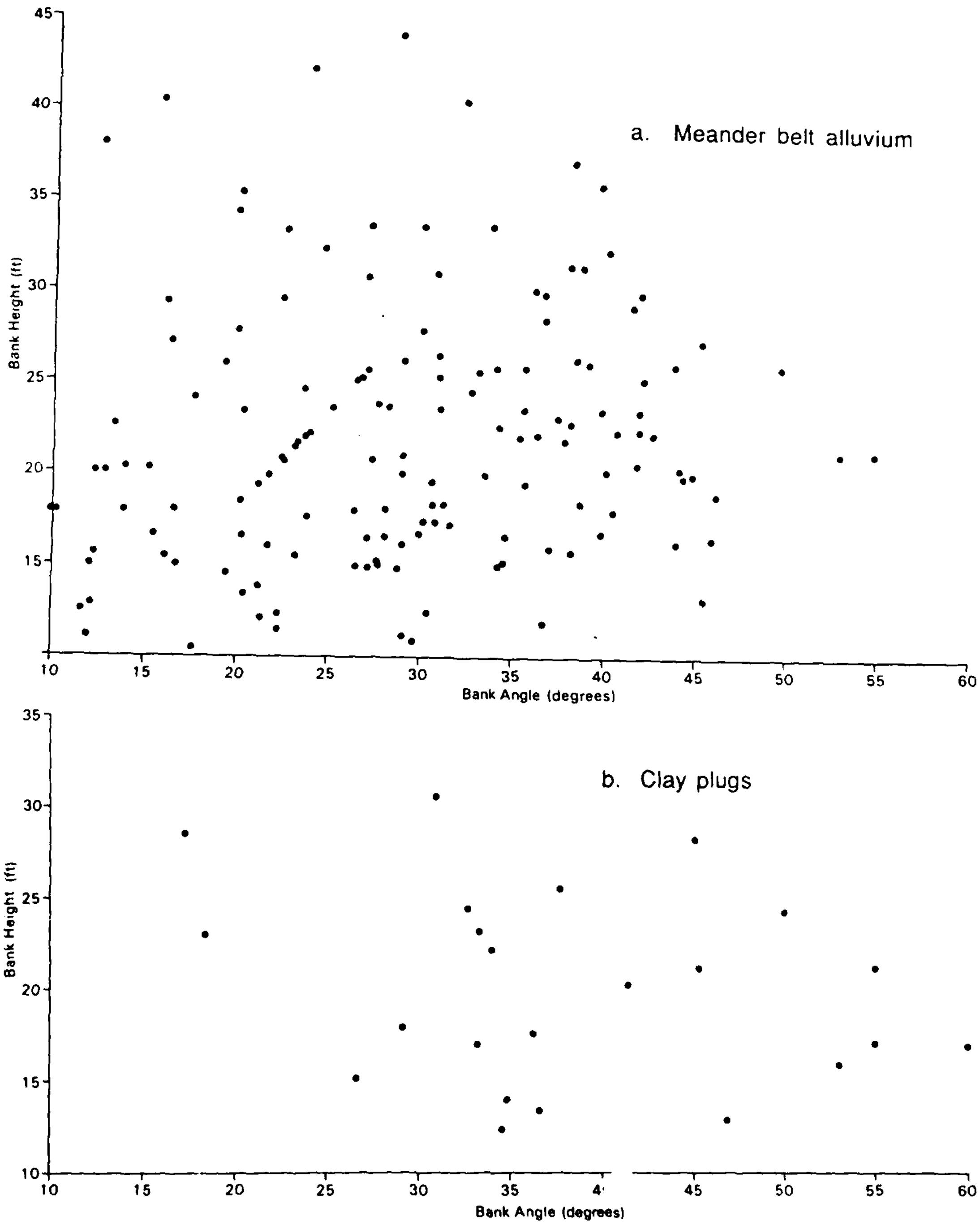
Secondly, the survey represents a snap-shot of the banks at a particular moment in time. It is not possible to know whether the geometry of the bank at that time was very stable, or close to failure. It is impossible to know to what extent the surveyed bank was composed of low-angle slump material that had not yet been removed by the flow and was masking the angle of the intact bank. Consequently, the data cannot be used to test the model of bank stability rigorously.

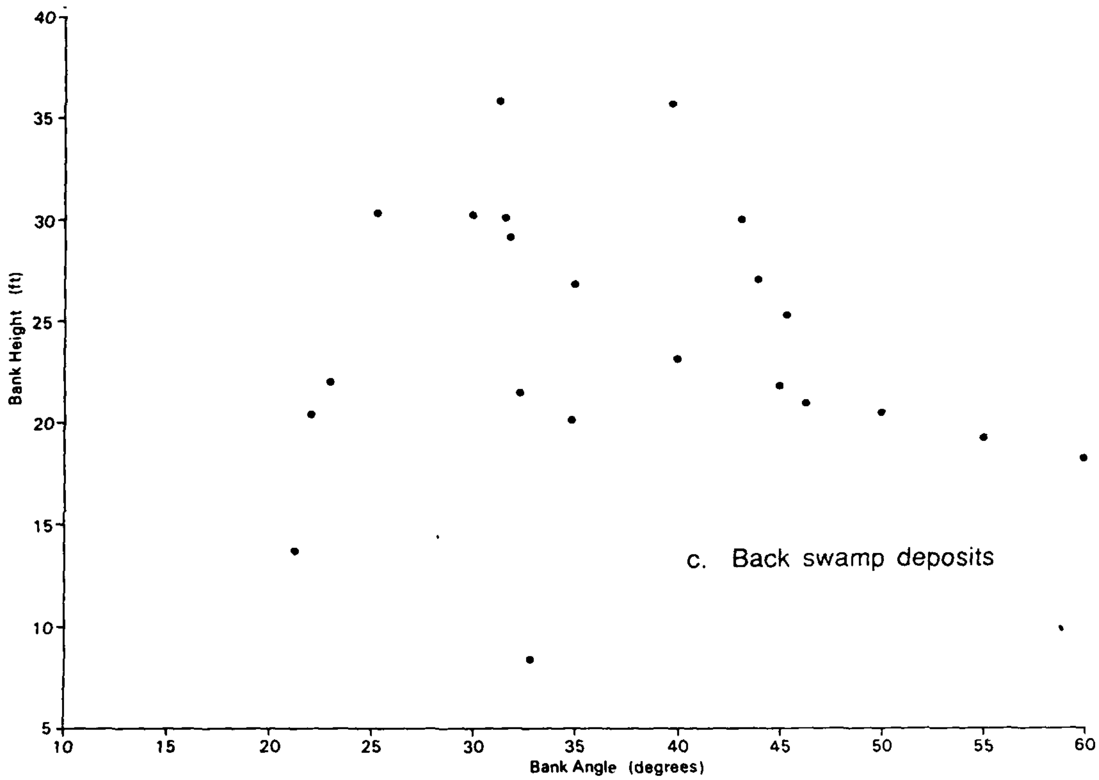
Nonetheless, the bank geometry data are useful in providing the opportunity for a coarse test of the bank stability analysis.

3.1.3 Geotechnical properties

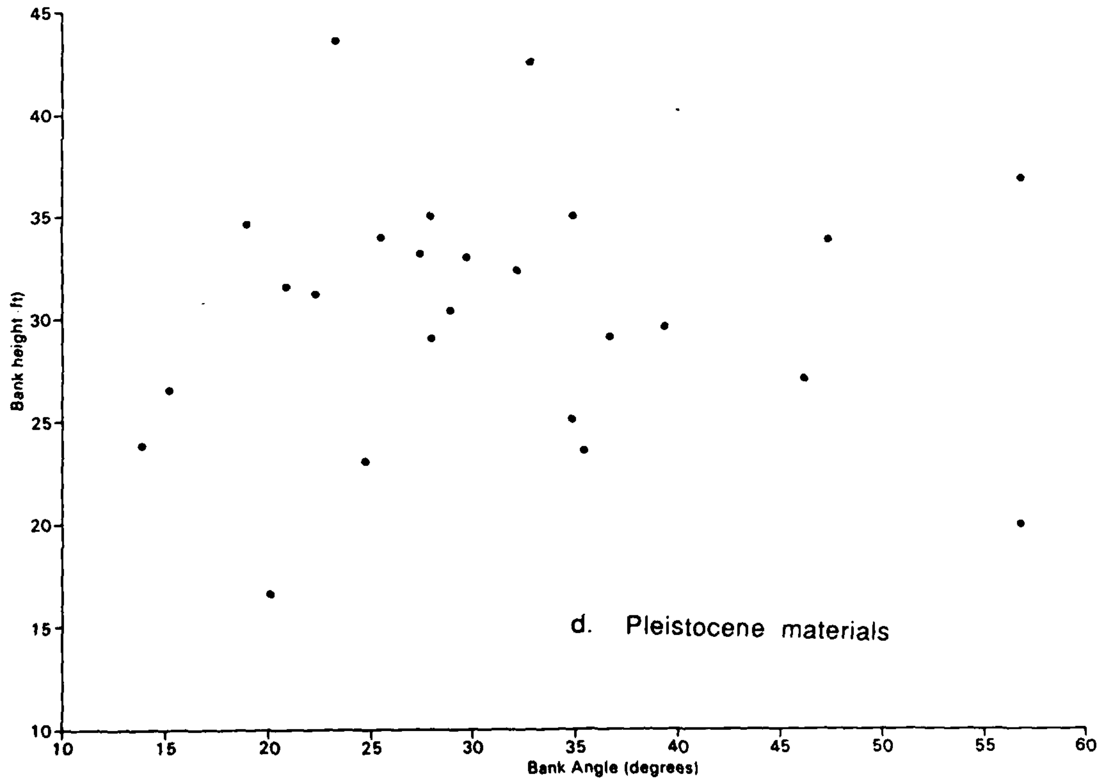
To allow application of the Osman-Thorne bank stability analyses, data were required on the engineering properties of the bank materials. These data were supplied by the Foundations and Materials Branch of the

Figure 2. Bank height and angle data from1980/1 hydrographic survey





Bank Height (ft)
40
35
30
25
20
15
10
5
10
15
20
25
30
35
40
45
50
55
60
Bank Angle (degrees)
c. Back swamp deposits



Bank height ft)
45
40
35
30
25
20
15
10
10
15
20
25
30
35
40
45
50
55
60
Bank Angle (degrees)
d. Pleistocene materials

Vicksburg District, US Army Corps of Engineers, on the basis of soils tests run on samples from site investigation borings all along the study reach. The data refer to "worst case" conditions and are listed in Table 1.

Table 1. Engineering Properties of Red River Sediments.

Sediment Type	Cohesion (lb/ft^2)	Friction Angle (degrees)	Bulk Unit Weight (lb/ft^3)
Clay	500	0	115
Silt	300	20	115
Sand	0	30	120
Back Swamp	400	0	115
Tertiary	1000	10	120

The form of the data supplied did not yield the characteristics of the clay plug and meander belt alluvium materials directly. Examination of the relevant size distribution curves from sampling of banks in the study reach suggested that the clay plugs are generally made up of about 50% clay and silt and 50% fine sand. Meander belt alluvium banks seem to be about 15% clay and silt, and 85% sand. On this approximate basis figures for the bank properties in Table 2 were generated by weighting the data in Table 1.

Table 2. Bank material properties on the Red River

Bank Material	Cohesion (lb/ft^2)	Friction Angle (degrees)	Bulk Unit Weight (lb/ft^3)
Meander Belt Alluvium	60	27	120
Clay Plug	200	20	118
Back Swamp	400	0	115
Tertiary	1000	10	120

3.1.4 Stability analyses

The Osman-Thorne analyses for rotational slip and slab-type failures was used to produce a table of values for the Stability Number (N_s) as a function of the bank material friction angle (ϕ) and the bank angle (i)

(Table 3). These data were used to produce the generalized, dimensionsless charts N_s of versus bank angle (i), shown in Fig. 3.

Table 3. Osman-Thorne Stability numbers for riverbanks

Friction Angle (°)	Bank Angle (°) 35	40	45	50	55	60	65	70	75	80	85	90
0	7.69	7.35	7.04	6.67	6.25	5.59	5.00	4.55	4.10	3.75	3.40	3.10
5	9.71	9.43	8.93	8.33	7.46	6.58	5.80	5.20	4.60	4.15	3.75	3.35
10	12.8	12.0	11.1	10.0	8.77	7.81	6.80	6.00	5.20	4.60	4.10	3.65
15	19.2	16.7	14.9	12.8	11.1	9.43	8.00	6.90	6.00	5.20	4.55	4.00
20	32.3	25.0	20.0	17.2	14.3	11.6	9.60	8.00	6.80	5.85	5.05	4.40
25	52.6	40.0	30.3	23.8	18.2	14.3	11.7	9.50	7.90	6.60	5.60	4.85
30	90.9	62.5	43.5	33.3	26.3	19.2	15.0	11.7	9.30	7.60	6.30	5.35

No reliable data on the characteristic tension crack depth for slab-type failures of the banks in the study reach were available and so a k value of 0.3 was used to generate the charts. Field inspection of failed banks suggested that this should be a reasonable approximation to actual values at failure. However, to test the sensitivity of the stability analysis to inaccuracy in the tension crack depth coefficient, the analysis was repeated for k values of 0.4 and 0.5. These values correspond to tension cracks to 30%, 40% and 50% of the bank height respectively, covering the range of crack depths observed in the field. The results for a friction angle of 20° are shown in Fig. 4. For the range of bank angles observed in the documentary and field studies (i = 35° to 75°) the variation in k produces only a small change in N_s. It can, therefore, be concluded that more precise identification of the tension crack depth is not essential in this study.

Figure 3. Generalized stability charts for riverbanks

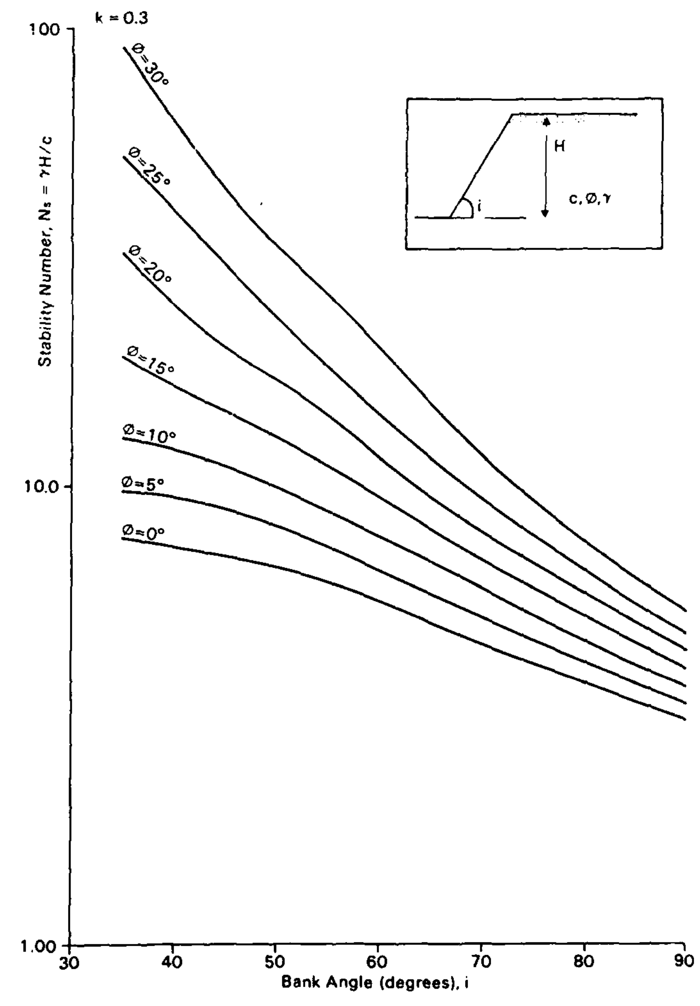
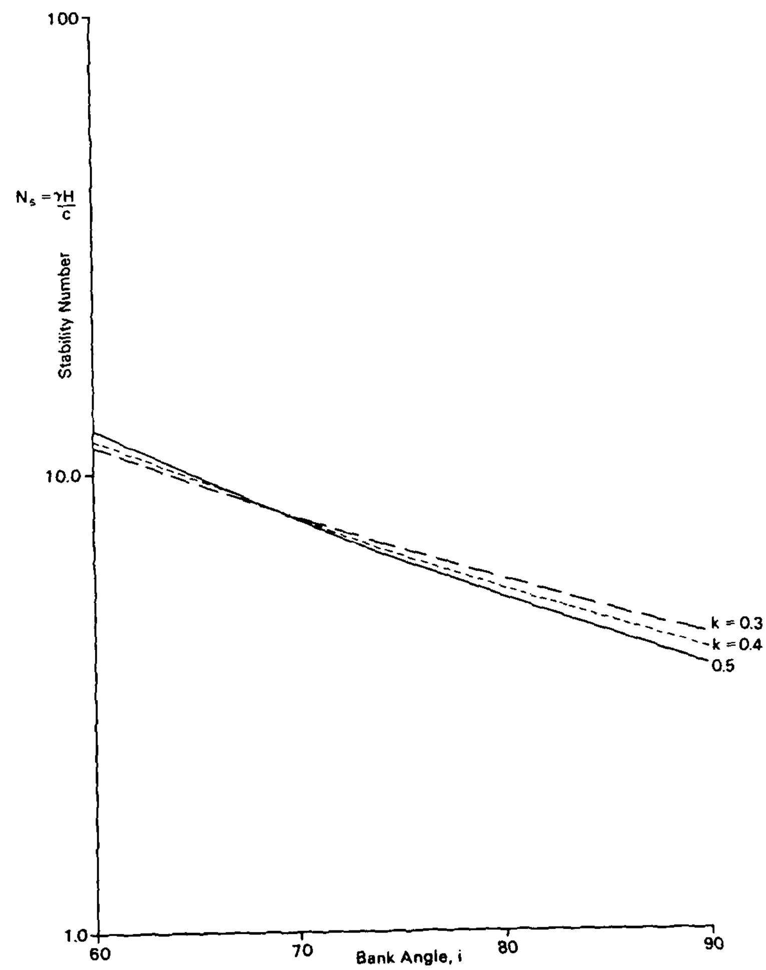


Figure 4. Sensitivity of stability number to tension crack index



The geotechnical data were used to calculate critical stability numbers and bank heights for the Red River banks. The results are tabulated by bank type in Table 4 and plotted in Fig. 5 a - d. The observed stability numbers and angles were plotted onto the dimensionless stability charts for comparison with the the lines of limiting stability derived from the theoretical analyses and the geotechnical data.

Table 4. Critical Osman-Thorne Stability Numbers and bank heights for Red River study reach

A. Meander Belt Alluvium							
Slab-type failures							
Bank Angle (degrees)	60	65	70	75	80	85	90
Critical Stabilty Number	16.5	12.9	10.3	8.5	7.0	5.85	5.48
Critical Height (ft)	8.3	6.5	5.1	4.2	3.5	3.0	2.5
Rotational Slip Failures							
Bank Angle (degrees)	35	40	45	50	55	60	
Critical Stabilty Number	65.5	48.5	35.3	27.2	21.2	16.5	
Critical Height (ft)	32.8	24.3	17.7	13.6	10.6	8.3	
B. Clay Plugs							
Slab-type failures							
Bank Angle (degrees)	60	65	70	75	80	85	90
Critical Stabilty Number	11.6	9.6	8.0	6.8	5.9	5.1	4.4
Critical Height (ft)	20.0	16.7	13.5	11.5	9.8	8.6	7.5
Rotational Slip Failures							
Bank Angle (degrees)	35	40	45	50	55	60	
Critical Stabilty Number	32.3	25.0	20.0	17.2	14.3	11.6	
Critical Height (ft)	54.7	42.4	33.9	29.2	24.2	19.7	
C. Back swamp deposits							
Slab-type failures							
Bank Angle (degrees)	60	65	70	75	80	85	90
Critical Stabilty Number	5.6	5.0	4.6	4.1	3.8	3.4	3.1
Critical Height (ft)	19.5	17.5	15.7	14.2	13.0	11.8	10.7
Rotational Slip Failures							
Bank Angle (degrees)	35	40	45	50	55	60	
Critical Stabilty Number	7.7	7.4	7.0	6.7	6.3	5.6	
Critical Height (ft)	26.7	25.6	24.5	23.2	21.7	19.5	

D. Pleistocene/Tertiary

Slab-type failures							
Bank Angle (degrees)	60	65	70	75	80	85	90
Critical Stabilty Number	7.8	6.8	6.0	5.2	4.6	4.1	3.7
Critical Height (ft)	65.0	57.0	50.0	43.5	38.5	34.5	30.5

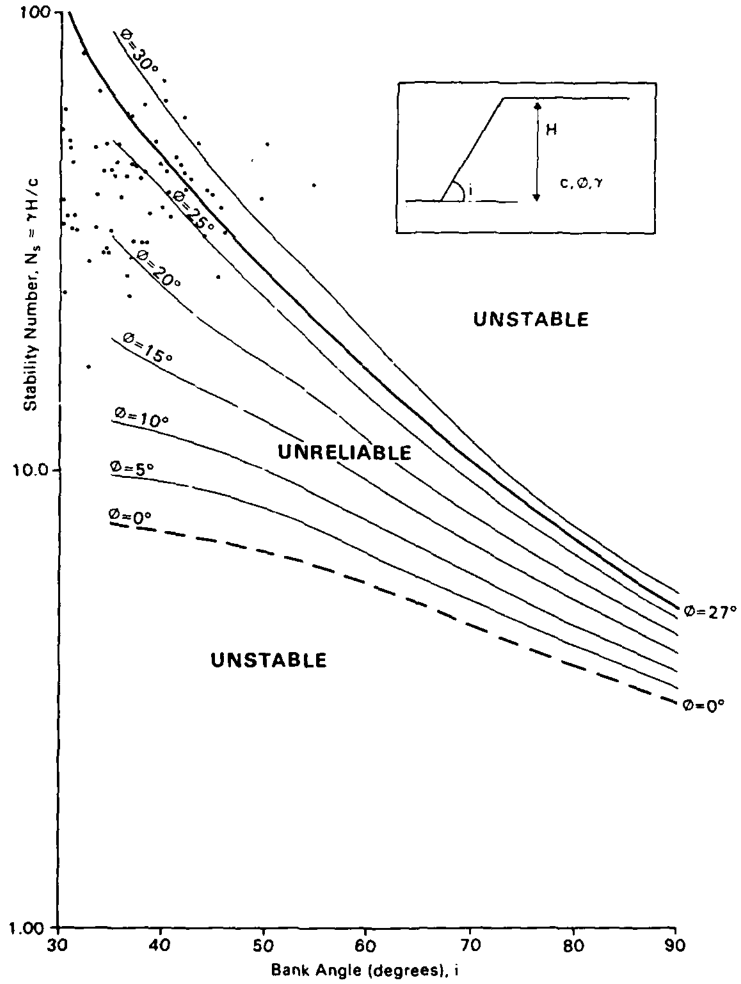
Rotational Slip Failures						
Bank Angle (degrees)	35	40	45	50	55	60
Critical Stabilty Number	12.8	12.0	11.1	10.0	8.8	7.8
Critical Height (ft)	106	100	92.5	83.3	73.1	65.0

3.1.5 Discussion of results - The data from the hydrographic survey generally support the results of the stability analyses. The most complete data set is that for the MBA banks, because the geotechnical proerties are well defined and there are a sufficient number of bank angle and height points to establish a trend. In theory, the points should plot in the "unreliable" zone of the stability chart as the survey data come from banks which were actively retreating, but were stable at the time of observation. This is in fact the case in Fig. 5a. Also, the line of limiting stability for worst case conditions should form an upper envelope to the data cloud, and this is true too. However, confirmation that Fig. 5a is a true representation of the stability of banks formed in MBA materials in the study reach requires data from banks having angles steeper than 50^{o}. In view of the limitations on bank data derived from hydrographic surveys, field measurements are probably the best way to obtain these data.

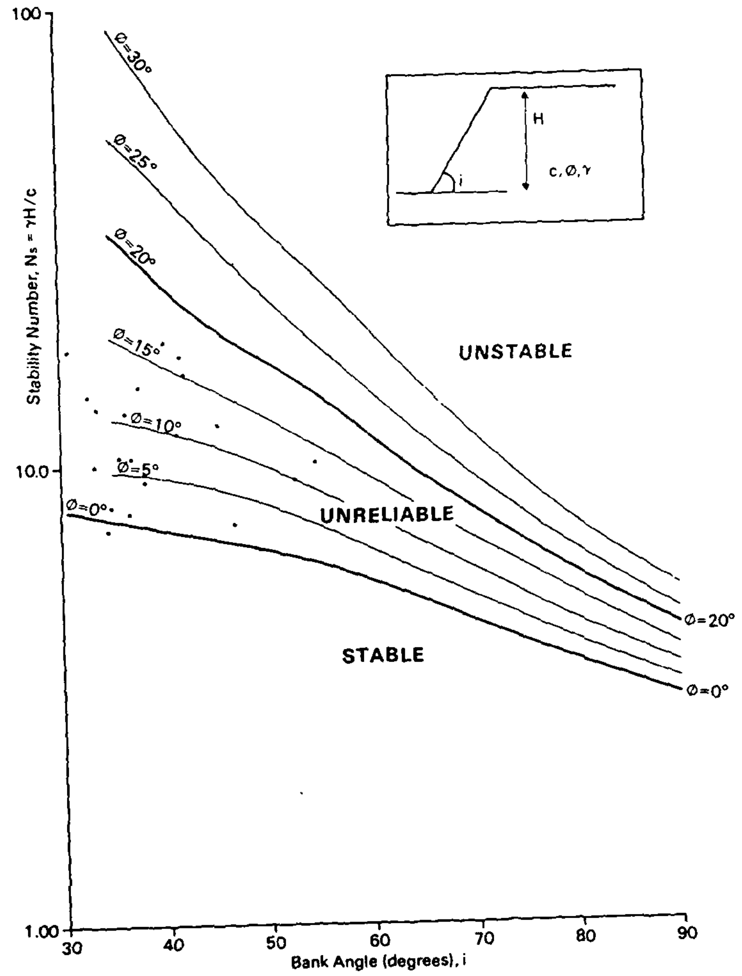
The results for clay plug banks (Fig.5b) also support the form of the stability chart. Most banks plot in the "unreliable" zone, as expected, and the trend of the limiting stabilty line does follow that of the data. However, the line looks a little high, suggesting that the friction angle of 20^{o} approximated from the geotechnical data might be an over-estimate. The stability chart distribution indicates that a friction angle of 15^{o} to 17^{o} might be more appropriate. More data are required to confirm this, especially for steep banks ($i > 50^{o}$).

The Back Swamp Deposit stabilty chart (Fig. 5c) shows only "stable" and "unstable" zones. The "unreliable" zone is absent because the geotechnical data supplied by the Foundations and Materials Branch specify a zero friction angle for worst case conditions. Field data are sparce for banks of this type, but those available suggest that the friction angle of the BSD materials may have been underestimated. An operational value of 5^{o} might be appropriate. Alternatively, the cohesion might be a little high. Decreasing the assumed cohesion by a relatively small proportion would

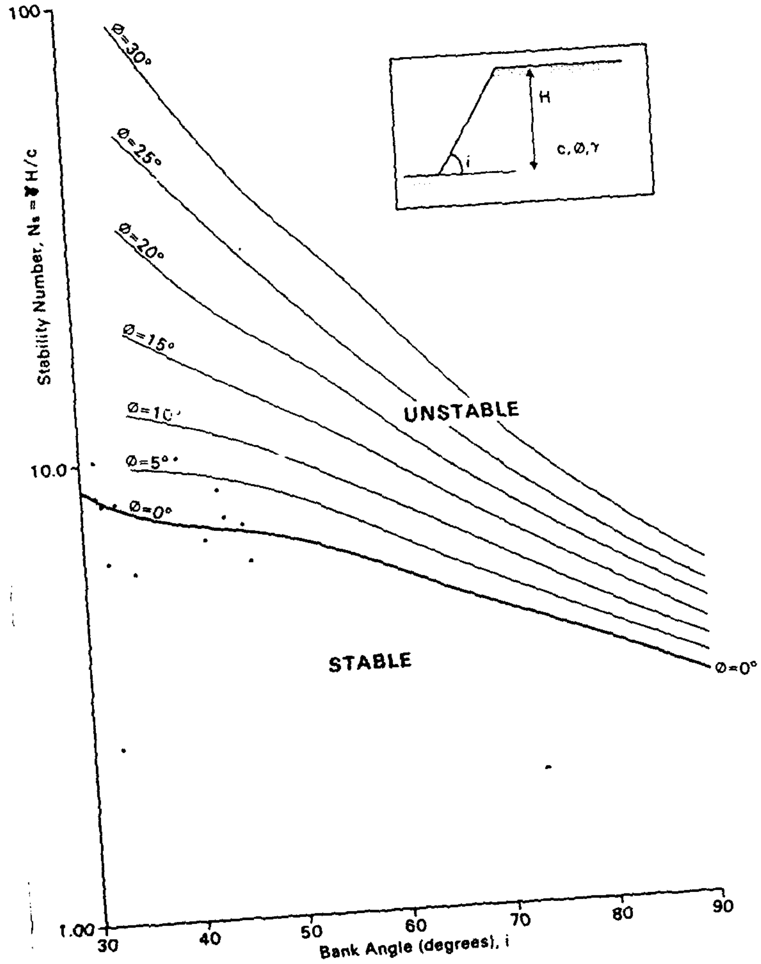
Figure 5. Stabilty charts for Red River banks formed in:-
a. Meander belt alluvium
b. Clay plugs
c. Back swamp deposits
d. Pleistocene materials



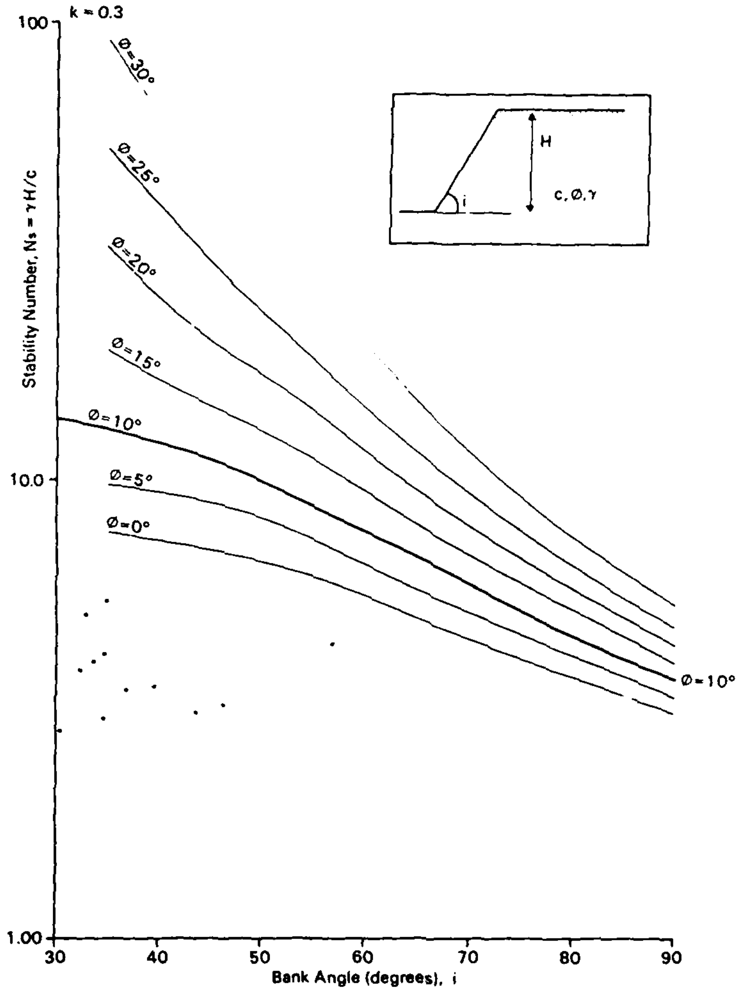
a. Meander belt alluvium


100
10.0
1.00
Stability Number, Ns = γH/c
Ø=30°
Ø=25°
Ø=20°
Ø=15°
Ø=10°
Ø=5°
Ø=0°
Ø=20°
Ø=0°
H
c, Ø, γ
i
UNSTABLE
UNRELIABLE
STABLE
30
40
50
60
70
80
90
Bank Angle (degrees), i

b. Clay plugs



c. Back swamp deposits



d. Pleistocene materials

bring the points just below the line of limiting stabilty for a friction angle of zero. More data are required across the full range of bank angles to resolve this issue.

The Pleistocene plot is the least satisfactory of the four (Fig. 5d). The data are so sparce that no firm conclusions can be drawn, but it appears that the cohesion value suggested by the Foundations and Materials Branch (1000 lb/ft^2) is much too high for use in analysing riverbank stability. The explanation for this statement is that although the value of 1000 lb/ft^2 is representative of the strength of these materials in the ground, it is an overestimate of their strength in a riverbank, where they are subject to weathering, weakening processes and tensile cracking due to stress relief at the bank face.

I believe that an operational cohesion of around 400 - 500 lb/ft^2 would better represent the PI riverbank materials. This would rank them close to, but somewhat stronger than the Back Swamp Deposits, which does not seem unreasonable.

In conclusion, the bank stability analyses of Osman and Thorne (1988) do appear to be applicable to the banks of the Red River in the study reach, although more field data on bank angles and heights in the various bank units are required to confirm this. The analyses highlight the fact that the geometry of the banks is a function of their geotechnical properties, and suggests that retreating banks are maintained close to their limiting geometry with respect to mass failure under gravity. This confirms that bank retreat in the study reach takes place by fluvial erosion of the bank to a limiting state, followed by mass failure under worst case conditions. Basal clean-out of slump debris then occurs, prior to further erosion of intact bank materials and subsequent failures.

3.1.6 Distribution of bank retreat

Bank erosion on the Red River in the study reach is mostly associated with meander evolution. Reconnaissance trips by boat made at low flow allowed reaches of eroding bank to be identified. The distribution of erosion within a bend depends mostly on the radius of curvature to width (R_c/w) ratio.

In "conventional" bends, the locus of bank erosion is located at the outer bank at, or a little downstream of, the meander exit. In this respect, conventional bends are those with radius of curvature to width (R_c/w) ratios greater than about 2, which through time are growing in amplitude by lateral erosion, and are migrating by downstream progression.

However, this is by no means the only form of meander present in the study reach. Several meanders have very low R_c/w ratios of the order of unity. These bends are found where a meander comes up against a resistant outer bank material, so that its normal growth and/or progression are disrupted. Examples of such situations occur where a meander reaches the outer limit of the current alluvial meander belt and impinges on older and more resistant terrace deposits, or where a clay plug within the alluvial deposits is encountered. In these very tight bends, the distribution of bank erosion is quite different from that in the conventional meanders. Bank erosion is concentrated at the inner bank, the outer bank being an area of flow separation and sediment deposition at formative flows. This leads to bench or berm building at the outer bank, a tendency for the bend to reduce rather than increase its amplitude with time, and more rapid downstream progression of the up-valley limb of the meander than the down-valley limb, leading to neck cut-off in due course. In geomorphic terms, the meander works its way around the obstruction presented by the resistant material at the outer bank. As a result, the distribution of bank erosion and the pattern of bend evolution are closely related to the distribution of clay plugs within the meander belt, and the occurrence of terraces. These terrace deposits consist of two major categories of material: Backswamp Deposits in a terrace associated with the 19th century flood plain, and much older deposits of Pleistocene and Tertiary age in terraces and in the valley sides above the valley floor (WET, 1987a).

The type and distribution of material encountered in the banks of an active meander bend exert strong influences on bend erosion and progression. In the case of the Red River in the study reach, a thorough knowledge of the distribution of terrace deposits, and to a lesser degree clay plugs, is therefore central to explaining and predicting channel evolution and, hence, bank erosion sediment yield. This is recognised by some engineers in the LMK and at WES, but the geomorphic significance of bank materials and their distribution must be stated again and again if it is to be established more widely.

3.2 River Bend Studies

3.2.1 River Bend Geometry Data

Data from the 1980/81 hydrographic survey were used to characterize the three-dimensional geometry of meander bends and crossings between Index and Shreveport. The complete set of data that was compiled is listed in Table 5.

Not every bend could be used. Some were rejected because of their complex geometry, location near a channel confluence, or due to uncertainties either concerning the nature of the outer bank materials or date of stabilization by revetment construction.

Table 5. Bend and crossing geometry data for the Index-Shreveport Reach from the 1980/81 Hydrographic Survey

RED RIVER MEANDER GEOMETRY — INDEX TO SHREVEPORT REACH — 1980 HYDROGRAPHIC SURVEY

A	B	C	D	E	F	G	H	I	J	K	L	M
	(Bend Geometry Parameters)								(Upstream Crossing Parameters)			
Location River Mile	Bend Radius (feet)	Width (feet)	Arc Angle (degrees)	Max. Sc. Loc River Mile	Max. Sc. Elev (ft NGVD)	Ave. Sc. Elev (ft NGVD)	2yr. flow (ft NGVD)	Outer Bank Type	Us X Loc River Mile	Max. Us. Elev (ft NGVD)	Ave. Us. Elev (ft NGVD)	2yr. flow (ft NGVD)
422.50	4000.00	1000.00	160.00	421.60	236.00	241.83	266.48	M	423.63	244.30	252.48	268.03
420.00	3500.00	1183.00	190.00	419.54	226.50	236.90	264.91	R	421.17	244.30	249.55	266.15
416.00	3500.00	1025.00	180.00	415.56	231.90	235.01	261.26	C	417.27	239.10	247.93	262.87
413.00	2500.00	993.00	150.00	412.68	225.50	232.88	258.59	R	414.37	238.00	246.63	260.14
411.00	5000.00	968.00	110.00	409.90	230.00	232.14	256.06	M	412.09	236.00	245.24	258.05
407.00	2500.00	1083.00	100.00	407.00	221.80	225.84	252.62	M	407.39	233.20	239.83	253.10
406.00	3750.00	1475.00	110.00	406.17	224.00	227.18	251.59	M	406.80	231.30	239.38	252.37
404.60	1500.00	1050.00	100.00	404.83	216.30	221.33	249.94	M	405.40	229.60	239.29	250.45
402.00	1500.00	725.00	100.00	401.74	206.60	208.46	246.14	M	402.61	220.50	234.00	247.21
401.08	7000.00	1000.00	45.00	401.38	212.50	215.31	245.69	R	401.54	212.50	227.32	245.89
398.50	2750.00	1175.00	110.00	398.28	208.20	212.64	242.39	C	399.07	222.20	228.04	243.13
397.00	3000.00	1083.00	120.00	396.25	211.70	215.48	240.62	R	397.39	222.30	227.46	241.56
394.45	2500.00	1200.00	140.00	394.73	205.70	209.95	239.45	P	395.42	218.90	226.56	239.98
392.50	3000.00	1050.00	115.00	392.28	205.50	209.41	237.58	R	393.19	213.20	226.00	238.27
391.50	3000.00	925.00	150.00	390.30	203.30	208.78	235.69	C	391.85	216.30	222.71	237.25
389.50	3000.00	788.00	110.00	389.00	201.20	207.34	234.00	R	389.93	213.10	217.60	235.21
387.00	5750.00	950.00	45.00	387.87	205.90	207.90	233.43	M	388.44	208.00	217.91	233.76
386.00	4000.00	1068.00	90.00	385.38	199.70	204.68	231.66	R	386.48	204.80	216.05	232.57
384.50	3500.00	975.00	90.00	384.29	196.30	201.66	230.76	R	385.20	207.60	216.41	231.51
383.50	2000.00	875.00	125.00	383.00	198.60	203.72	229.70	M	383.60	210.90	214.35	230.19
382.00	2000.00	825.00	130.00	382.00	191.50	198.56	229.13	R	382.73	207.30	212.81	229.54
377.84	2500.00	1000.00	60.00	377.84	188.60	193.36	227.28	M	381.74	192.70	211.21	228.98
376.00	10000.00	1100.00	35.00	375.86	187.60	199.95	226.54	M	376.26	205.30	210.76	226.70
374.50	9000.00	1100.00	30.00	374.66	194.20	199.52	225.96	C	375.16	203.00	209.14	226.26
373.50	2000.00	1175.00	90.00	373.59	193.40	195.58	225.26	R	373.84	200.00	209.21	225.38
372.00	3000.00	863.00	90.00	371.90	[illegible]	195.82	224.03	R	372.40	199.70	205.51	224.38
370.50	2500.00	925.00	120.00	370.42	[illegible]	190.88	222.99	R	371.20	195.70	205.84	223.54
367.50	3500.00	925.00	140.00	376.73	187.60	190.72	220.34	R	368.55	198.50	205.83	221.41
365.00	3500.00	1175.00	140.00	364.94	187.10	190.77	216.76	R	366.39	198.20	202.97	218.60
361.40	4500.00	1050.00	140.00	361.75	187.80	189.93	214.66	R	362.24	192.70	199.75	214.98
360.00	2000.00	850.00	120.00	360.05	177.40	184.83	213.05	R	360.64	191.00	197.77	213.64
359.00	4000.00	900.00	110.00	358.38	183.20	186.55	211.57	R	359.18	192.00	195.78	212.18
356.50	4000.00	975.00	140.00	355.75	177.80	184.76	209.72	R	357.43	190.80	192.53	210.94
354.00	4500.00	1100.00	110.00	354.52	170.60	182.10	208.86	R	355.10	187.60	195.18	209.27
353.50	9000.00	1200.00	35.00	353.53	181.20	183.90	208.17	M	353.60	187.80	192.16	208.22
352.50	3000.00	1300.00	180.00	351.96	176.80	180.91	206.78	C	353.00	185.10	194.22	207.80
351.22	2500.00	1150.00	170.00	351.00	170.80	177.18	205.85	M	351.66	185.30	192.52	206.49
349.00	3250.00	1000.00	200.00	348.77	175.00	178.89	203.68	M	349.82	183.70	189.29	204.70
347.50	2500.00	1125.00	180.00	347.82	163.70	172.86	202.74	R	348.05	179.40	187.81	203.15
345.00	5000.00	1100.00	140.00	344.99	172.80	176.48	199.99	M	346.32	178.20	185.37	201.18
342.00	3250.00	1125.00	130.00	343.45	168.10	175.85	197.69	B	342.80	176.60	184.05	198.57
340.50	2200.00	1050.00	180.00	340.47	164.20	169.58	197.11	M	341.30	173.20	182.87	197.59
339.00	3250.00	950.00	130.00	338.65	161.30	167.29	195.53	B	340.20	174.20	181.87	196.72
337.70	9750.00	1050.00	20.00	336.64	165.30	172.41	194.56	M	338.23	171.20	180.87	195.33
334.71	3000.00	1200.00	60.00	334.81	154.00	161.93	193.67	P	335.10	172.30	177.38	193.81
330.50	3000.00	1050.00	90.00	330.27	156.60	160.31	191.16	M	330.91	167.00	174.86	191.54
328.50	4500.00	1000.00	120.00	328.40	152.10	159.48	190.04	R	329.80	165.90	173.14	190.88
326.50	4000.00	1000.00	100.00	326.37	157.70	160.95	188.79	R	327.11	164.60	171.74	189.26
325.00	5500.00	1000.00	70.00	324.93	154.30	158.53	187.95	C	325.59	160.60	171.92	188.35
323.00	4000.00	1000.00	100.00	322.97	148.90	161.36	186.78	C	323.92	164.60	170.39	187.35
318.50	6000.00	1000.00	60.00	318.57	152.20	154.58	183.81	M	319.57	159.10	166.08	184.64
315.00	5500.00	1000.00	70.00	314.47	149.20	153.45	181.48	P	315.55	154.70	166.43	181.92
310.00	5500.00	1350.00	150.00	309.63	143.50	147.82	178.45	R	310.73	153.10	163.59	179.25
309.00	1000.00	1675.00	100.00	308.80	133.50	142.82	177.80	P	309.18	147.70	160.59	178.13
307.00	8000.00	1025.00	20.00	307.71	143.40	146.45	176.71	M	307.90	149.00	156.50	176.90
A	B	C	D	E	F	G	H	I	J	K	L	M
306.70	7000.00	800.00	50.00	306.38	143.00	145.84	175.38	P	307.04	150.60	155.04	176.04
304.00	7500.00	1100.00	60.00	304.19	142.60	146.28	173.79	R	305.91	152.20	156.01	174.94
302.36	4000.00	1100.00	170.00	301.54	137.00	142.78	171.54	B	302.99	150.10	154.97	172.99
299.00	6000.00	1150.00	170.00	298.71	139.10	142.90	169.85	P	300.67	147.00	154.37	170.83
294.00	7500.00	875.00	45.00	293.27	136.60	140.59	166.65	R	295.80	144.10	148.44	168.40
292.22	8500.00	1025.00	35.00	291.74	134.90	139.09	165.47	M	292.41	143.00	147.17	165.99
290.00	5000.00	1675.00	90.00	289.81	129.80	135.29	164.38	C	291.17	142.00	148.82	165.03
288.00	4000.00	1000.00	120.00	287.60	131.40	136.58	163.25	R	289.14	139.30	147.69	164.00
287.00	2500.00	800.00	120.00	286.29	130.20	131.94	162.62	M	287.10	137.10	146.86	163.01
285.00	7000.00	775.00	60.00	284.45	130.50	134.05	161.22	R	285.45	135.60	141.75	162.22
281.50	3000.00	1000.00	180.00	282.93	118.70	127.57	159.06	R	284.17	133.20	141.36	160.82
280.50	3500.00	800.00	190.00	279.52	118.40	125.60	154.23	R	281.74	133.60	135.29	157.38
278.50	2750.00	800.00	130.00	278.38	111.80	124.91	152.67	R	279.14	129.70	134.06	153.73
277.46	6250.00	800.00	85.00	277.23	110.10	122.14	151.08	R	278.00	125.70	134.84	151.79
276.50	2750.00	800.00	80.00	276.34	109.90	116.22	149.82	R	277.05	124.90	128.90	150.81

N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
Downstream Cro		ssing Parameters		All Bends						Revetted Bends				Alluvial Bends				Clay Pl	
Dn X Loc River Mile	Max.Dn.Elev (ft NGVD)	Ave.Dn.Elev (ft NGVD)	2yr Flow (ft NGVD)	Rc/w	Bend Dmax (feet)	Bend Dbar (feet)	Xing Dbar (feet)	BDm/XDb	BDb/XDb	Rc/w	BDm/XDb	BDb/XDb	Arc Angle (Degrees)	Rc/w	BDm/XDb	BDb/XDb	Arc Angle (Degrees)	Rc/w	BDm/XDb
421.17	244.30	249.58	266.16	4.00	30.48	24.65	16.06	1.90	1.53	.00	.00	.00	.00	4.00	1.90	1.53	160.00	.00	.00
419.06	243.80	250.66	264.55	2.96	36.41	28.01	15.25	2.39	1.84	2.96	2.39	1.84	190.00	.00	.00	.00	.00	.00	.00
415.30	237.00	245.18	261.02	3.41	29.36	26.25	15.39	1.91	1.71	.00	.00	.00	.00	.00	.00	.00	.00	3.41	1.91
412.09	236.00	245.24	258.06	2.52	33.09	25.71	13.17	2.51	1.95	2.52	2.51	1.95	150.00	.00	.00	.00	.00	.00	.00
409.17	235.80	240.69	255.89	5.17	26.06	23.98	13.71	1.90	1.75	.00	.00	.00	.00	5.17	1.90	1.75	110.00	.00	.00
406.80	231.30	239.38	252.37	2.31	30.88	26.78	13.13	2.35	2.04	.00	.00	.00	.00	2.31	2.35	2.04	100.00	.00	.00
405.40	229.60	239.29	250.65	2.54	27.59	24.41	12.18	2.27	2.00	.00	.00	.00	.00	2.54	2.27	2.00	110.00	.00	.00
404.08	224.80	235.65	248.95	1.43	31.64	28.61	12.22	2.59	2.34	.00	.00	.00	.00	1.43	2.59	2.34	100.00	.00	.00
401.54	212.50	227.32	245.90	2.07	39.84	37.68	15.90	2.49	2.37	.00	.00	.00	.00	2.07	2.49	2.37	100.00	.00	.00
400.06	224.10	226.10	244.00	7.00	33.19	30.38	18.24	1.82	1.67	7.00	1.82	1.67	45.00	.00	.00	.00	.00	.00	.00
397.39	222.30	227.46	241.56	2.34	34.19	29.75	14.60	2.34	2.04	.00	.00	.00	.00	.00	.00	.00	.00	2.34	2.34
395.42	218.90	226.56	239.99	2.77	28.98	25.14	13.77	2.10	1.83	2.77	2.10	1.83	120.00	.00	.00	.00	.00	.00	.00
391.96	215.00	224.39	238.87	2.08	33.75	29.50	13.88	2.44	2.13	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
391.80	216.30	222.71	237.25	2.86	32.08	28.17	13.41	2.39	2.10	2.86	2.39	2.10	115.00	.00	.00	.00	.00	.00	.00
389.93	213.10	217.60	235.21	3.24	32.39	26.91	16.08	2.01	1.67	.00	.00	.00	.00	.00	.00	.00	.00	3.24	[illegible]
388.44	208.00	217.90	233.76	3.81	32.80	26.66	16.74	1.96	1.59	3.81	1.96	1.59	110.00	.00	.00	.00	.00	.00	.00
387.50	210.90	216.62	233.20	6.05	27.53	25.53	16.22	1.70	1.57	.00	.00	.00	.00	6.05	1.70	1.57	45.00	.00	.00
385.20	207.60	216.41	231.51	3.75	31.96	26.96	15.81	2.02	1.71	3.75	2.02	1.71	90.00	.00	.00	.00	.00	.00	.00
383.60	210.90	214.35	230.19	3.59	34.56	29.10	15.47	2.23	1.88	3.59	2.23	1.88	90.00	.00	.00	.00	.00	.00	.00
382.73	207.30	212.81	229.55	2.29	31.10	25.90	16.29	1.91	1.59	.00	.00	.00	.00	2.29	1.91	1.59	125.00	.00	.00
381.74	192.70	211.22	228.99	2.42	37.63	30.57	17.25	2.18	1.77	2.42	2.18	1.77	130.00	.00	.00	.00	.00	.00	.00
377.06	204.20	209.62	227.02	2.50	38.68	33.92	17.59	2.20	1.93	.00	.00	.00	.00	2.50	2.20	1.93	60.00	.00	.00
375.16	203.00	209.14	226.26	9.09	28.94	26.59	16.53	1.75	1.61	.00	.00	.00	.00	9.09	1.75	1.61	35.00	.00	.00
373.84	200.00	209.21	225.39	8.18	31.76	26.44	16.65	1.91	1.59	.00	.00	.00	.00	.00	.00	.00	.00	8.18	1.91
373.09	198.30	209.07	224.86	1.70	31.86	29.68	15.98	1.99	1.86	1.70	1.99	1.86	90.00	.00	.00	.00	.00	.00	.00
371.20	195.70	205.84	223.97	3.48	41.63	28.21	18.00	2.31	1.57	3.48	2.31	1.57	90.00	.00	.00	.00	.00	.00	.00
369.94	199.80	206.70	222.66	2.70	36.09	32.11	16.83	2.14	1.91	2.70	2.14	1.91	120.00	.00	.00	.00	.00	.00	.00
366.39	198.20	202.97	218.61	3.78	32.74	29.62	15.61	2.10	1.90	3.78	2.10	1.90	140.00	.00	.00	.00	.00	.00	.00
364.41	196.30	204.33	216.41	2.98	29.66	25.99	13.86	2.14	1.88	2.98	2.14	1.88	140.00	.00	.00	.00	.00	.00	.00
360.64	191.00	197.77	213.64	4.29	26.86	24.72	15.55	1.73	1.59	4.29	1.73	1.59	140.00	.00	.00	.00	.00	.00	.00
359.18	192.00	195.78	212.18	2.35	35.65	28.22	16.14	2.21	1.75	2.35	2.21	1.75	120.00	.00	.00	.00	.00	.00	.00
357.[illegible]	188.10	193.94	210.74	4.44	28.37	25.02	16.60	1.71	1.51	4.44	1.71	1.51	110.00	.00	.00	.00	.00	.00	.00
355.10	187.60	195.18	209.27	4.10	31.92	24.96	16.25	1.96	1.54	4.10	1.96	1.54	140.00	.00	.00	.00	.00	.00	.00
353.60	187.80	192.16	208.22	4.09	30.26	26.76	15.08	2.01	1.78	4.09	2.01	1.78	110.00	.00	.00	.00	.00	.00	.00
353.00	185.10	194.22	207.80	7.50	25.97	24.27	14.82	1.75	1.64	.00	.00	.00	.00	7.50	1.75	1.64	35.00	.00	.00
351.66	185.30	192.52	206.49	2.31	29.98	25.87	13.78	2.18	1.88	.00	.00	.00	.00	.00	.00	.00	.00	2.31	2.18
350.66	183.10	190.77	205.73	2.17	35.05	28.67	14.37	2.44	2.00	.00	.00	.00	.00	2.17	2.44	2.00	170.00	.00	.00
348.05	179.40	187.81	202.97	3.25	28.68	24.79	15.29	1.88	1.62	.00	.00	.00	.00	3.25	1.88	1.62	200.00	.00	.00
347.04	178.30	186.96	202.02	2.22	39.04	29.88	15.20	2.57	1.97	2.72	2.57	1.97	180.00	.00	.00	.00	.00	.00	.00
344.18	177.70	184.04	199.47	4.55	27.19	23.51	15.62	1.74	1.51	.00	.00	.00	.00	4.55	1.74	1.51	140.00	.00	.00
341.30	173.20	182.87	197.59	2.89	29.59	21.84	14.62	2.02	1.49	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
340.20	174.20	181.87	196.72	2.10	32.91	27.53	14.79	2.23	1.86	.00	.00	.00	.00	2.10	2.23	1.86	180.00	.00	.00
338.23	171.20	180.87	195.33	3.42	34.23	28.24	14.66	2.34	1.93	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
336.53	171.10	179.24	194.50	9.29	25.26	22.15	14.86	1.70	1.49	.00	.00	.00	.00	9.29	1.70	1.49	20.00	.00	.00
333.84	171.60	175.94	193.21	2.50	39.67	31.74	16.85	2.35	1.88	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
329.80	165.90	173.14	190.88	2.86	34.56	30.85	17.21	2.01	1.79	.00	.00	.00	.00	2.86	2.01	1.79	90.00	.00	.00
327.11	164.60	171.74	189.27	4.50	37.94	30.56	17.64	2.15	1.73	4.50	2.15	1.73	[illegible]	.00	.00	.00	.00	.00	.00
325.59	160.60	171.92	188.35	4.00	31.09	27.84	16.98	1.83	1.64	4.00	1.81	1.64	160.00	.00	.00	.00	.00	.00	.00
323.92	164.60	170.39	187.35	5.50	33.65	29.42	16.70	2.03	1.76	.00	.00	.00	.00	.00	.00	.00	.00	5.50	2.02
322.13	161.80	169.88	186.28	4.00	37.88	25.42	16.68	2.27	1.52	.00	.00	.00	.00	.00	.00	.00	.00	4.00	2.27
317.86	158.10	163.82	183.22	6.00	31.61	29.23	18.96	1.67	1.54	.00	.00	.00	.00	6.00	1.67	1.54	60.00	.00	.00
312.87	156.80	160.33	180.81	5.50	32.20	28.03	17.99	1.79	1.56	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
309.18	147.70	160.59	178.13	4.07	35.95	30.63	16.60	2.17	1.85	4.07	2.17	[illegible]	150.00	.00	.00	.00	.00	.00	.00
307.90	149.00	156.50	176.90	.60	44.30	34.98	18.97	2.34	1.84	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
307.04	150.60	155.04	176.04	7.80	33.31	30.26	20.70	1.61	1.46	.00	.00	.00	.00	7.80	1.61	1.46	20.00	.00	.00
N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
305.91	152.20	156.01	174.94	8.73	32.38	29.54	19.97	1.62	1.48	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
302.99	150.10	154.97	172.99	6.82	31.19	27.51	18.48	1.69	1.49	6.82	1.69	1.49	60.00	.00	.00	.00	.00	.00	.00
300.67	147.00	154.37	170.83	3.64	34.54	28.76	17.24	2.00	1.67	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
297.85	145.70	148.20	169.42	5.22	30.75	26.95	18.84	1.63	1.43	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
292.60	142.70	147.98	166.14	8.57	30.05	26.06	19.06	1.58	1.37	8.57	1.58	1.37	45.00	.00	.00	.00	.00	.00	.00
291.17	142.00	148.82	165.03	8.29	28.57	26.38	17.52	1.63	1.51	.00	.00	.00	.00	8.29	1.63	1.51	35.00	.00	.00
289.14	139.30	147.69	164.00	2.99	34.58	29.03	16.26	2.12	1.79	.00	.00	.00	.00	.00	.00	.00	.00	2.99	2.12
287.10	137.10	146.86	163.01	4.00	31.85	26.67	16.23	1.96	1.64	4.00	1.96	1.64	120.00	.00	.00	.00	.00	.00	.00
285.72	133.80	137.66	162.35	3.13	36.42	30.68	20.42	1.78	1.50	.00	.00	.00	.00	3.13	1.78	1.50	120.00	.00	.00
284.17	133.20	141.36	160.82	9.03	30.72	27.17	19.97	1.54	1.36	9.03	1.54	1.36	60.00	.00	.00	.00	.00	.00	.00
282.02	132.40	136.11	157.48	3.00	40.36	31.49	20.42	1.98	1.54	3.00	1.98	1.54	140.00	.00	.00	.00	.00	.00	.00
279.14	129.70	134.06	153.70	4.38	35.83	28.63	20.87	1.72	1.37	4.38	1.72	1.37	190.00	.00	.00	.00	.00	.00	.00
277.61	129.60	132.56	151.59	3.44	40.87	27.76	19.35	2.11	1.43	3.44	2.11	1.43	130.00	.00	.00	.00	.00	.00	.00
277.05	124.90	128.90	150.81	7.81	30.96	28.92	19.43	1.59	1.49	7.81	1.59	1.49	25.00	.00	.00	.00	.00	.00	.00
276.06	126.60	131.85	149.45	3.44	39.92	33.60	19.76	2.02	1.70	3.44	2.02	1.70	80.00	.00	.00	.00	.00	.00	.00

	AI	AJ	AK	AL	AM	AN	AO	AP	AQ
	..................]	[...........Back Swamps			..................]	[...........Pleistocene			....
b/XDb	Arc Angle (Degrees)	Rc/w	BDm/XDb	BDb/XDb	Arc Angle (Degrees)	Rc/w	BDm/XDb	BDb/XDb	Arc Angle (Degrees)
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.71 1.71	180.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
04 2.04	110.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	2.08	2.44	2.13	140.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
67 1.67	150.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
00	.00	.00	.00	.00	.00	.00	.00	.00	.00
59 1.59	30.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
88 1.88	180.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	2.89	2.02	1.49	130.00	2.89	2.02	1.49	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	3.42	2.34	1.93	130.00	3.42	2.34	1.93	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	2.50	2.35	1.88	60.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
0	.00	.00	.00	.00	.00	.00	.00	.00	.00
76 1.76	70.00	.00	.00	.00	.00	.00	.00	.00	.00
52 1.52	100.00	.00	.00	.00	.00	.00	.00	.00	.00
	.00	.00	.00	.00	.00	.00	.00	.00	.00
	.00	.00	.00	.00	.00	5.50	1.79	1.56	70.00
	.00	.00	.00	.00	.00	.00	.00	.00	.00
	.00	.00	.00	.00	.00	.60	2.34	1.84	100.00
	.00	.00	.00	.00	.00	.00	.00	.00	.00

AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ
	.00	.00	.00	.00	.00	8.75	1.62	1.48	50.00
	.00	.00	.00	.00	.00	.00	.00	.00	.00
	.00	3.64	2.00	1.67	170.00	3.64	2.00	1.67	.00
	.00	.00	.00	.00	.00	5.22	1.63	1.43	170.00
	.00	.00	.00	.00	.00	.00	.00	.00	.00
	.00	.00	.00	.00	.00	.00	.00	.00	.00
79 1.79	90.00	.00	.00	.00	.00	.00	.00	.00	.00
	.00	.00	.00	.00	.00	.00	.00	.00	.00
	.00	.00	.00	.00	.00	.00	.00	.00	.00
	.00	.00	.00	.00	.00	.00	.00	.00	.00
	.00	.00	.00	.00	.00	.00	.00	.00	.00
	.00	.00	.00	.00	.00	.00	.00	.00	.00
	.00	.00	.00	.00	.00	.00	.00	.00	.00
	.00	.00	.00	.00	.00	.00	.00	.00	.00
	.00	.00	.00	.00	.00	.00	.00	.00	.00

Each bend that was used is defined by the location of its apex in river miles on the 1980/81 hydrographic survey.

Definition of the geometry of a channel (width, depth, radius of curvature and so on) demands that some consistant value be used for the discharge. Usually, the dominant discharge is used for this purpose. On this basis the 2-year flow was selected as the representative flow for this study, as analysis of longterm records from the gauge at Shreveport by Biedenharn et al. (1987) has established this as approximating the dominant flow for this reach of the Red River. All measurements of channel geometry and scour depth are then referenced to the 2-year flow line, as established from runs of the HEC-2 water surface profile program undertaken by the LMK in the course of their own hydraulic investigations. Bed elevations (ft above NGVD) were converted to depths below the 2 year water surface profile using a computer program.

The nature of the outer bank at each bend was established from geological maps and field surveys. The distributions of meander belt, clay plug, back swamp and Pleistocene materials in the flood plain and terraces of the Red River Valley in this reach. were marked onto aerial photographic mosaics. Corp's records were used to establish the extent and date of installation of revetments in the study reach. Using the marked aerial photographs, bends were classified by outer bank type as being free meanders (M), clay plug (C), back swamp (B), Pleistocene (P), or revetted (R) in column I of Table 5.

To investigate whether the nature of the outer bank in a bend does influence the scour depth, the base data were processed to produce the parameters listed in Table 6.

Table 6. Parameters used in Table 5 to analyse bend scour

Column	Definition of parameter	Symbol
R	The radius of curvature to width ratio	R_c/w
S	Maximum scour depth at the bend	BD_{max}
T	Mean scour depth at the bend	BD_{bar}
U	Mean depth at the upstream and downstream crossings	XD_{bar}
V	Ratio of max. bend scour depth to mean crossing depth	BD_{max}/XD_{bar}
W	Ratio of mean bend scour depth to mean crossing depth	BD_{bar}/XD_{bar}

The purpose of dividing bend scour depths by the average of the mean channel depth at the crossings immediately upstream and downstream of the bend in question (XD_{bar}) was to remove any scale effects. This produced the two measures of the excess depth at a bend over that at a straight reach, due to bend scour listed in columns V and W of Table 5.

3.2.2 Bend Scour Depth - Outer Bank Type Relations

To investigate relations between the scour depth and the outer bank type at bends, the data in columns V and W were split by bank type (column I) and listed separately for each bank type in columns X to AQ of Table 5.

Two sets of non-linear regression analyses were then performed on the data. In the first case R_c/w was the independent variable and BD_{max}/XD_{bar} was the dependent variable. A number of regression approaches were tried and that giving the best coefficients of determination was selected. This involved the use of the parameter (R_c/w-2) to predict scour pool depth at a bend. Some justification of the use of this parameter is relevant here.

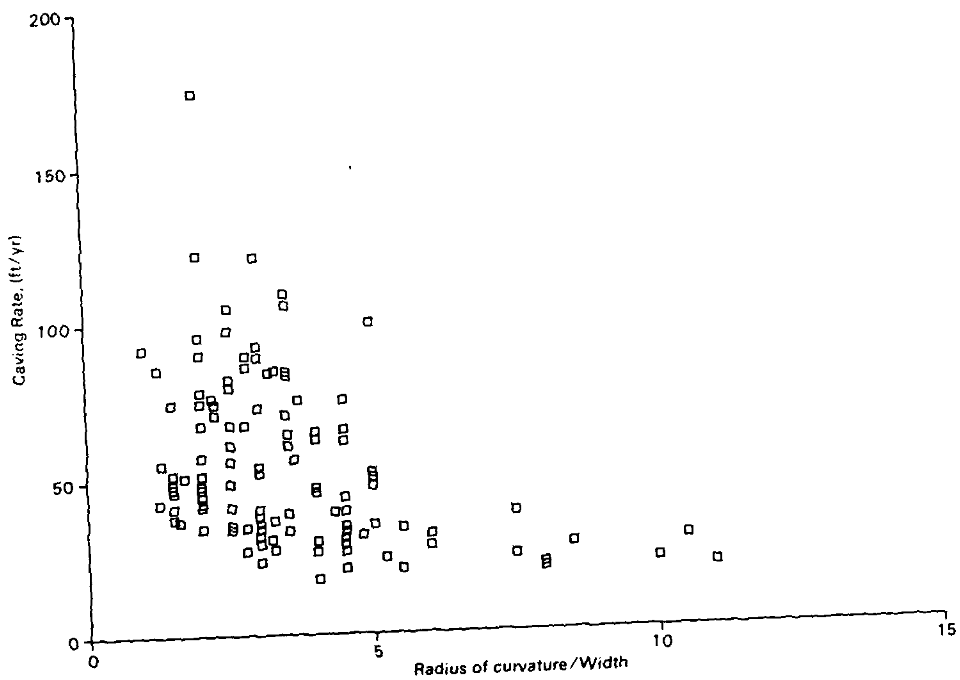
A great body of theoretical, experimental and observational evidence indicates that as the ratio of radius of curvature to width in a bend is reduced to a value of about two, gross changes occur to the flow patterns in the bend. These result in marked differences in the bend's morphology and its rate and direction of migration. Notable among the researchers to investigate these phenomena are Bagnold (1960) and Nansen and Hickin (1983). A plot of bank caving rate versus R_c/w for the study reach produced at LMK (Biedenharn et al., 1989) confirms the significance of a ratio of two here also (Fig. 6). This plot shows that the upper bound of caving rate **increases** steeply as R_c/w reduces from 5 to 2. However, further reduction to a value below two produces a rapid **reduction** in the upper bound for the caving rate. This is probably associated with the generation of large separation zones at the outer bank, and a switch to erosion of the inner bank, as observed by Reid (1984) on the Connecticut River.

On the basis of the available evidence I decided that it was justifiable to take $R_c/w = 2$ as a lower boundary to the regression analysis, and this was supported by the good fit between the data and the regression lines that resulted. The results are listed in Table 7.

In the second case (R_c/w - 2) was the independent variable and BD_{bar}/XD_{bar} was the dependent variable. The results are listed in Table 8.

In neither case could a regression be carried out for the Back Swamp bends because there were only three bends in this catagory and this is too few for meaningful results. The numbers of bends in the Clay Plug and

Figure 6. Plot of caving rate of outer bank versus radius of curvature to width ratio for the study reach of the Red River (from Biedenharn et al, 1989).



Pleistocene catagories are also undesirably low, but are acceptable. The two groups of primary interest in this study, Free Meanders and Revetted Meanders, had 20 and 31 observations respectively: ample to perform analyses of this type.

Table 7. Regression Results for Maximum Bend Scour Depth

Regression Equation $(BD_{max}/XD_{bar}) = a + b\,Log_e\,(R_c/w - 2)$

Outer bank Type	Correlation Coefficient (r)	Coefficient of Determination (r^2)	a	b	No. of Points
Free Meander	0.90	0.81	1.98	-0.17	20
Clay Plug	0.65	0.42	2.12	-0.10	8
Back Swamp	---	---	---	---	3
Pleistocene	0.85	0.72	2.07	-0.20	8
Revetted	0.83	0.69	2.15	-0.27	31
All Bends		0.64	2.07	-0.19	66

Table 8. Regression Results for Mean Bend Scour Depth

Regression Equation $(BD_{bar}/XD_{bar}) = a + b\,Log_e\,(R_c/w - 2)$

Outer bank Type	Correlation Coefficient (r)	Coefficient of Determination (r^2)	a	b	No. of Points
Free Meander	0.79	0.63	1.75	-0.13	20
Clay Plug	0.77	0.60	1.78	-0.12	8
Back Swamp	---	---	---	---	3
Pleistocene	0.82	0.67	1.73	-0.15	8
Revetted	0.67	0.45	1.76	-0.16	31
All Bends	0.74	0.55	1.75	-0.14	66

All of the r values listed in Tables 7 and 8 are statistically significant at the 95% level of significance. Examination of the correlation coefficients shows that in all cases except that for Clay Plug bends, r for the maximum bend scour is higher than that for the mean bend scour, indicating a stronger relation between maximum pool depth in a bend and R_c/w for a given outer bank type, than between mean pool depth and R_c/w. The clay plug result probably stems from the fact that plugs are of limited extent and the maximum scour depth in a these bends is located at, or just downstream of, the clay plug and is only indirectly controlled by the bend geometry. Hence, it is the position of the clay plug in the bend, rather than the bend geometry, that primarily controls maximum scour depth, and since this is not accounted for in the regression analysis, it lowers the correlation coefficient. Mean scour depth is much less affected, because this parameter depends less on the position of the clay plug.

Values of the coefficient of determination (r^2) indicate the proportion of the total variance explained by the regression equation. Unexplained variance is attributable to errors and to the effects of other independent variables. It was suspected that some variance could be explianed by the different arc angles of the bends. However, no improvement in explanation could be found when this variable was added to the analysis.

3.2.3 Generalized Bend Scour Depth Relations

This study was concerned primarily with the effect of outer bank stabilization on scour depth in bends and so generalization of the results is limited to these two categories of bend. In any case, the sparcity of data for bends of the other types limits the conclusions that can be drawn concerning them. The base data for free meanders and revetted bends are plotted in Figs. 7 and 8. The regression lines and equations from Tables 7 and 8 are also shown. However, it is important to view these results in the light of relations for all outer bank types, and Fig. 9 summarizes these results.

The regression lines in Fig. 9 show a systemmatic and explainable distribution. For tight meander bends the ratio of bend maximum scour depth to mean crossing depth increases from alluvial meanders to clay plugs to pleistocene to revetted bends. This is exactly as expected from the results of Friedkin (1945) and the theories of Thorne and Osman (1988). The slopes of the best fit lines for alluvial, Pleistocene and revetted bends also increase systemmatically, so that the lines converge as R_c/w increases. This shows that the influence of outer bank properties decreases as bends become longer and less strongly curved. In fact the line for revetted bends actually crosses the other two at R_c/w of about 5. The reason for this is that in relatively straight revetted reaches the cross-section tends to be more trapezoidal, so that depth is more uniform

Figure 7. Graphs of maximum bend scour depth to mean crossing depth ratio versus radius of curvature to width ratio for a) Free alluvial meanders and b) Revetted bends.

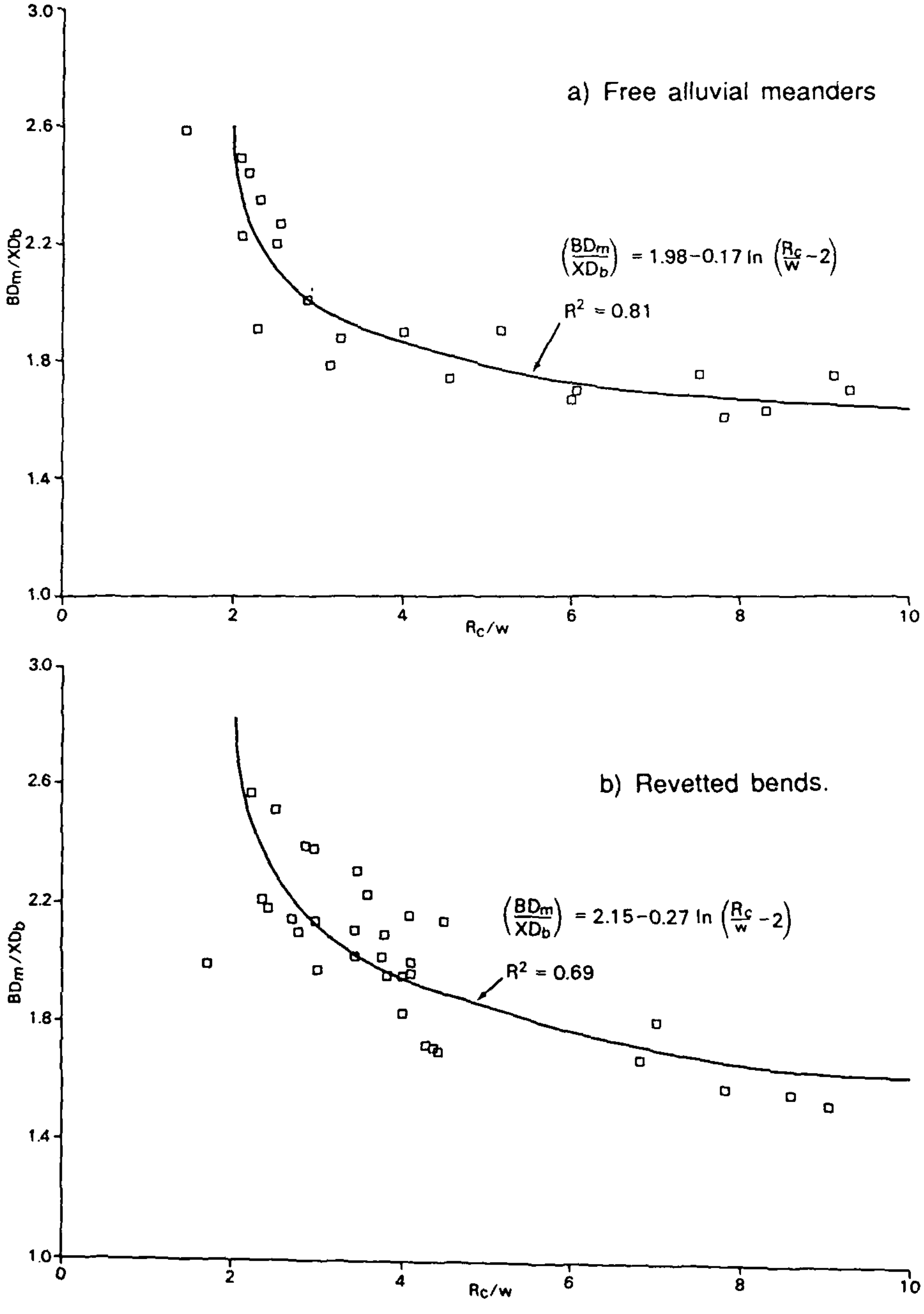
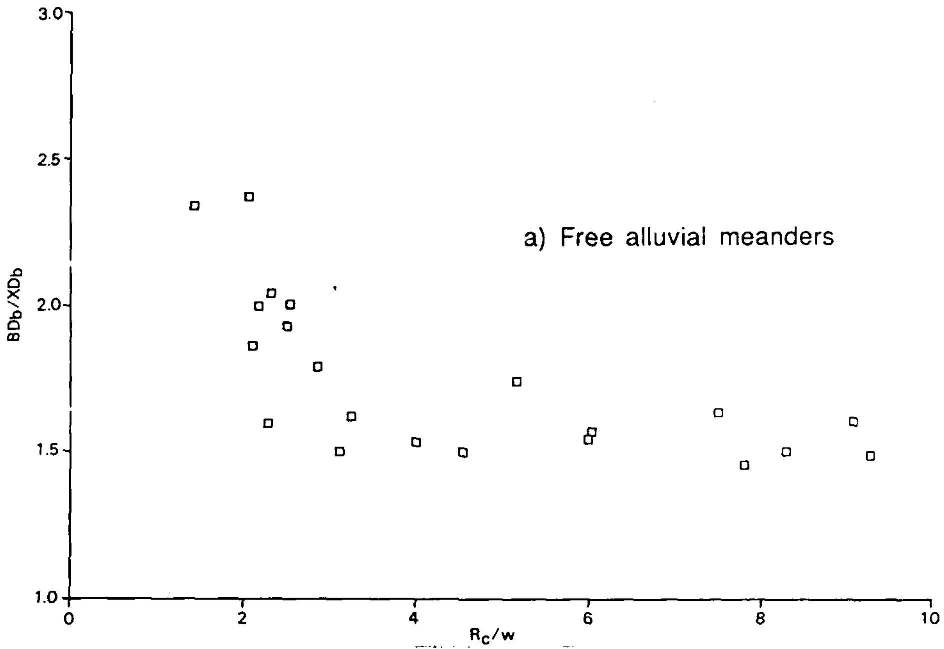


Figure 8. Graphs of mean bend scour depth to mean crossing depth ratio versus radius of curvature to width ratio for a) Free alluvial meanders and b) Revetted bends.



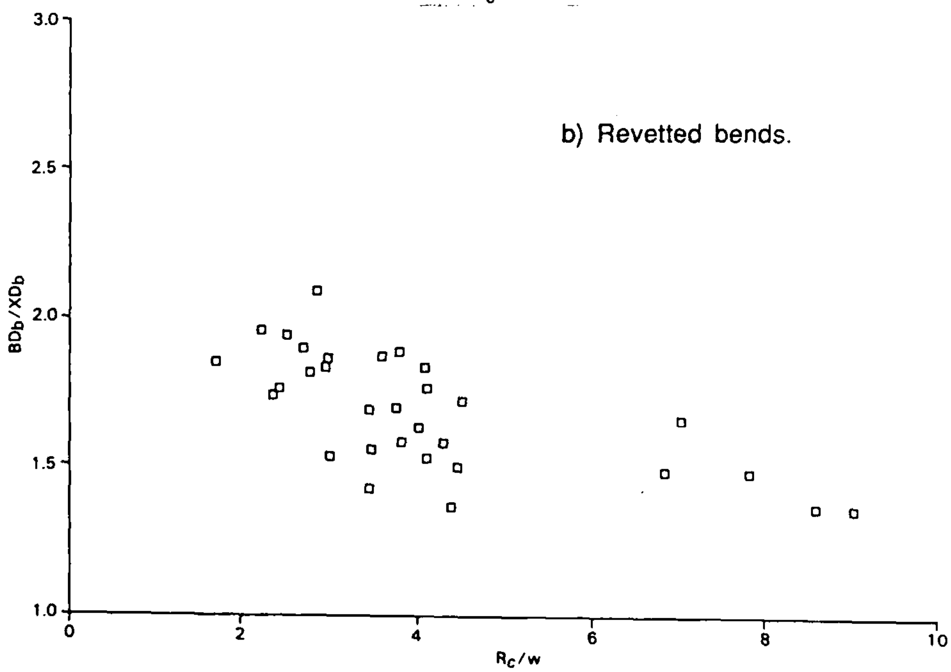
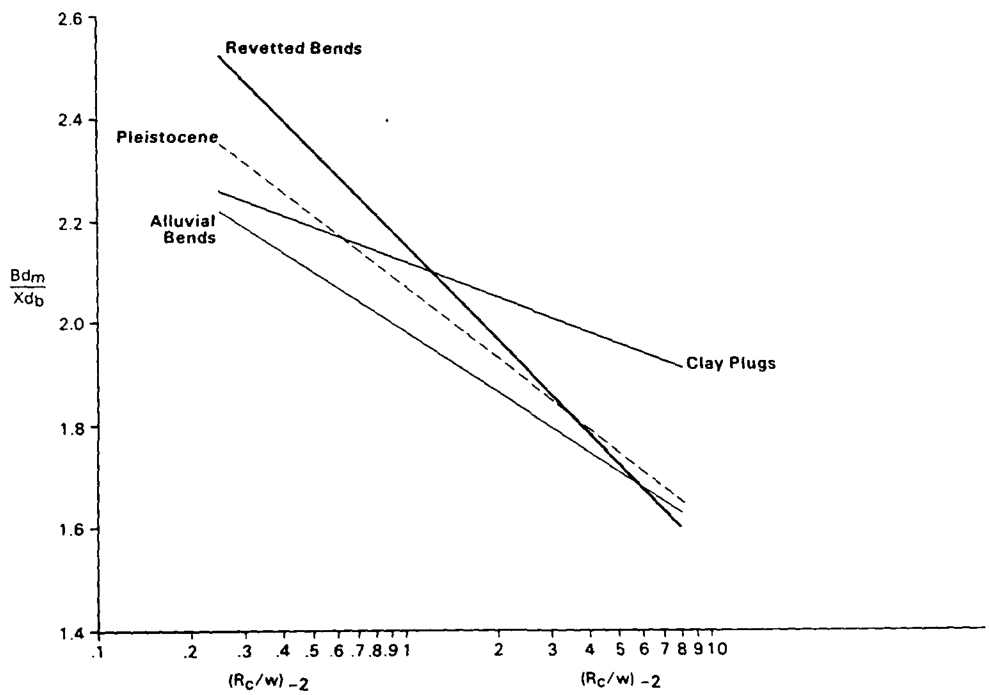


Figure 9. Best fit regression lines for mean bend scour depth to mean crossing depth ratio versus radius of curvature to width ratio for all bend types.



than in an equivalent alluvial reach. Consequently, the ratio of maximum to mean depth in the revetted channel is actually lower than that in the alluvial reach, although average depth may itself be greater.

The best fit line for clay plug bends cuts across the other lines at a much lower slope, showing that in these bends the ratio of maximum scour depth to mean crossing depth decreases much less quickly with increasing R_c/w. This is a result of the nature of clay plugs. These are resistant deposits of limited extent in the outer bank. They characteristically produce "hard points" that limit the rate of bank retreat, but also disturb the flow and generate local scour of the bed adjacent to, or just downstream of the plug. In such bends, the deepest pool is associated with local scour at the clay plug and this may be at any point in the bend, depending on the location of the hard point. By contrast, the deepest pool in free meanders was invariably close to or just downstream of the bend exit, where fully developed bend flow attacks the outer bank and the bed at the bank toe. Hence, maximum scour depth at a clay plug bend depends strongly on the depth of local scour generated by the hard point or points in the bend, rather than the bend geometry itself. It is quite possible for deep scour to be generated by a particularly effective hard point in a long radius bend, or possibly even in a straight reach in some circumstances, and this is the cause of the low gradient of the clay plug line in Fig.9.

The plots in Figs. 7 and 8 show that both maximum and mean scour pool depths in revetted bends are greater than in free meanders of the same R_c/w.

In the case of maximum bend scour depth, for a typical bend with an $R_c/w = 3$, and a mean crossing depth (XD_{bar}) of 17ft, the maximum scour pool depth would be 33.7ft in a free meander but 36.6ft in a revetted meander. This represents an increase of about nine percent. For a long radius bend, with $R_c/w = 6$, the relevant depths would be 29.6ft and 30.2ft respectively, a difference of only 2 percent. But for a tight meander, with $R_c/w = 2.1$, the scour depths rise to 40ft and 47ft respectively, an increase of 17 percent for the revetted bend. As a rule of thumb, the maximum scour depth in revetted bends might be expected to be about ten to fifteen percent greater than that for the equivalent free meander, the difference decreasing as R_c/w increases.

From the plot and relation for free meanders it appears that the scour pool depth approaches a value of about 1.5 times the mean depth as the R_c/w becomes large (for example $R_c/w = 25$) - that is in almost straight reaches. Comparison of maximum to mean depths for straight reaches (crossings) yields a ratio of 1.46 for 140 data points. This indicates that the scour pool/mean depth ratio for a bend does approach that for a straight reach as bend effects disappear, as would be expected. For revetted bends the ratio of scour pool depth to mean depth at a high value of R_c/w = 25, is 1.3, suggesting that in nearly straight reaches there is a tendency for revettted reaches to have more uniform cross-sections than free alluvial reaches. This is again as expected.

The distribution of results is very similar when mean bend scour depth is considered, but the differences are less marked (Fig. 8 and Table 8). For the typical bend, with R_c/w = 3, the mean bend pool depth in a free meander is 29.8ft, increasing only to 30ft for a revetted bend. For long bends (R_c/w = 6), the relevant depths are 26.7ft and 26.2ft respectively. For a tight bend (R_c/w = 2.1), the depths are 34.8ft and 36.2ft, a difference of 4 percent. Hence, it this study suggests that increases in mean scour depth in revetted versus free bends only become appreciable at very low values of R_c/w.

It should remembered that all these depths are based on bed elevations observed in a low flow hydrographic survey. Usually, the bed is scoured deeper during high flows, with scouring being strongest in the pools of bends and weakest at crossings. Consequently, since no allowance has been made for bend scour during floods, these figures are probably conservative. It would be interesting to predict the distribution of scour during floods using a suitable mobile-bed model for water and sediment routing and then add the effects of flood scouring onto the figures here. However, this would require considerable research effort.

The results of this part of the study do seem to make sense and support the hypothesis that revetted bends tend to have deeper scour pools than the equivalent free meanders, the extra depth being a systemmatic function of R_c/w. However, the coefficients of determination indicate that other factors also may be important and could contribute significantly to scour pool depth variation.

3.2.4 Crossing Depth - Outer Bank Type Relations

The aim here was to investigate whether crossing depths were increased in revettted reaches compared to values in alluvial reaches. The data in Table 5 were used to determine average values for maximum and mean crossing depth in free alluvial reaches and between consecutive, revetted bends for the whole study reach of the Red River. The resulting averages were:

Free Alluvial Reaches	XD_{max} = 23.60ft	XD_{bar} = 16.55ft
Revetted Reaches	XD_{max} = 23.83ft	XD_{bar} = 16.62ft
Ratio Free/Revetted	**0.99**	**0.98**

The two ratios are essentially equal to unity. On this basis there is no evidence to support the hypothesis that crossing depths in revetted reaches are significantly greater than those in the equivalent free, alluvial reach. The imression gained when traveling down the river by boat is that some crossings between revetments are both shorter and deeper than those between free meanders, but that in others the low-flow channel is choked with sediment. Possibly, the distribution of crossing depths in revetted reaches is bi-modal and this distribution is being masked by simple averaging. A more thorough statistical analysis of the data would be required to resolve this question.

3.3 Prediction of Channel Response

It appears that bank stabilization in bends of the Red River should be expected to add between 5 and 20% to the scour pool depths in those bends. This is not a negligible amount and it could add significantly to the sediment load output from a bend while the additional scouring is actually occurring. Once the bed has been reprofiled, the sediment output should decrease somewhat, but it seems unlikely that it will ever return to its pre-revettment level.

Transmission of the sediment downstream involves its movement through further crossings and bends. The evidence is that increased storage at crossings will not occur, but that neither will increased scour. Storage in subsequent bends is strictly limited also. This is the case because point bar growth in revetted bends ceases when retreat of the outer bank opposite prevents further advance of the inner bank, through constricting the flow. From these considerations, it must be concluded that the sediment derived from extra pool scouring will make its way downstream through the reach relatively quicky for bed material load, arriving in due course at the head of the navigation reach.

The calibre of the sediment yielded from bed scour rather than bank erosion may be quite different. Generally, bed sediment in this reach of the Red River is much coarser than bank sediment. Consequently, although its movement will be quick for bed material load, it will still move more slowly than the present 'wash load' from bank sediments and will, therefore, take longer to reach the navigation reach. Also, its coarser size will cause it to be deposited in different locations in the system. Specifically, bed material load should be expected to form deltaic type deposits at the head of navigation pools, while the wash load falls out in lock chambers and behind dams. If it is lock and dam sedimentaion that poses the more serious problem, then this should be a benefit.

If the stabilization of the banks also involves significant an increase in channel slope and a decrease in flow resistance through the reduction of sinuosity by channel re-alignment, then sediment transmission will be accelerated. In addition, there may be further bed scour associated with increased transport capacity due to the increased slope and decreased resistance, even after that caused by bank stabilization has ceased. The question of channel response to re-alignment is an important one, but it is beyond the scope of this study.

3.4 Philip Bayou Re-Alignment

Data on the Philip Bayou re-alignment were supplied by the LMK at the end of my stay in Vicksburg. These data should be sufficient to apply the Osman-Thorne model for bank stability response to changes in channel hyrdaulics and sediment load (Osman and Thorne, 1988). It was envisaged at the outset that this would involve continued work at Queen Mary College after the end of this project, and this was clearly stated in the original proposal. Work is progressing slowly and will be commumicated to the Corps of Engineers in due course. The Corps commitment to supporting this effort was limited to supplying the necessary data, and this has been done in a timely fashion.

IV CONCLUSIONS AND RECOMMENDATIONS

1. Bank retreat in the study reach takes place by basal erosion which triggers mass failure, followed by basal clean-out of failed material.
2. Bank geometry and processes are affected by bank material properties. On this basis banks may be classified according to their origin as: meander belt alluvium; clay plug; back swamp deposit; and Pleistocene.
3. The dominant failure mechanisms are rotational slips and slab or toppling failures. Generally, slabs occur on meander belt alluvium and clay plug banks and rotational slips on back swamp and Pleistocene banks, but with many exceptions to this rule.
4. The stability analyses of Osman and Thorne can be used to predict the critical geometry (height and angle) for the different bank types using reasonable estimates of the engineering properties provided by the Foundations and Materials section of LMK. However, it appears that the operational strength of the Pleistocene materials is about half that suggested.
5. A relation can be demonstrated between outer bank properties and scour depth at a bend. Scour depth increases as bank resistance

increases from alluvium to clay plug to Pleistocene to revetted banks. The data were insufficient to analyse back swamp banks in this regard.

6. Generally, the influence of outer bank properties on scour depth increases as the radius of curvature to width ratio decreases (Fig. 9). There is a marked discontinuity at $R_c/w = 2$, consistent with the observation made elsewhere that the flow pattern at a bend changes radically in such tight bends. $R_c/w = 2$ therefore forms a real physical boundary to the applicability of these results.
7. Maximum scour depths in revetted bends are greater than those in the equivalent free meanders as shown in Fig. 7. As a rule of thumb, maximum depths are 5% to 20% greater.
8. Mean scour depths are similarly, but less markedly increased (Fig. 8).
9. No effect of outer bank revettments on crossing depths could be discerned in this study.
10. Stabilization of the remaining active meanders of the Red River in the study reach can be expected to promote bend scour and to increase both maximum and mean depths in pools at bends. The sediment so derived will be transmitted downstream to arrive in the navigation reach. Its coarser size will promote pool head deposition rather than sedimentation in locks and at dams.
11. Significant increase of slope and decrease of flow resistance caused by re-alignment of the channel could generate additional scour over and above that associated with bank stabilization alone. This should be taken into account when planning engineering measures in the reach if the aim is to reduce the sediment supply to the navigation reach.

V ACKNOWLEDGEMENTS

The work reported here was undertaken while the author was a visiting scientist at the Hydraulics Laboratory of the Waterways Experiment Station, Vicksburg, Mississippi. The help and encouragement of the staff at WES, and particularly Dr Bobby Brown and Terry Waller, is gratefully acknowledged. Much time was spent at the Vicksburg District Offices and there the staff of the Hydraulics Branch all lent me support and advice. I am particularly grateful to Phil Combs, David Biedenharn, Tim Hubbard, Charlie Little, Charlie Montague, John Watkins, Glenda Hill and Clara Pinkstone. My graduate students from Queen Mary College, Lisa Cheadle and Andrew Markham, both took time off from their own research projects to help me with this one, and their help was invaluable.

VI. LITERATURE CITED

Bagnold, R.A. (1960) "Some aspects of the shape of river meanders" US Geological Survey Professional Paper 282-E, pp 135-144.

Biedenharn, D.S., Combs, P.G., Hill, G.J., Pinkard, C.F. and Pinkstone, C.B. "Relationship between channel migration and radius of curvature on the Red River" ASCE Hydraulics Division, Proceedings of the National Conference on Hydraulic Engineering, New Orleans, August 1989.

Biedenharn, D.S., Little, C.D. & Thorne, C.R. (1987) "Magnitude and frequency analysis in large rivers" In, Hydraulic Engineering, Proc. of the Williamsburg Symposium, August 1987, ASCE, pp 782-787.

Friedkin, J.F. (1945) "A laboratory study of the meandering of alluvial rivers" US Army Corps of Enginers, Mississippi River Commission, Vicksburg, MS 39180, 40p.

McCall, E. (1988) "The attack on the Great River Raft" American Heritage of Invention & Technology, winter, 1988, pp 10-16.

Nanson, G.C. & Hickin, E.J. (1983) "Channel migration and incision on the Beatton River" Journal Hydraulic Engineering, ASCE, 109, pp 327-337.

Osman, A.M. and Thorne, C.R. (1988) " Riverbank stability analysis: Part I Theory", Journal of Hydraulic Engineering, ASCE, Vol 114, No.2, pp 125 - 150.

Raphelt, N.K. (1986) "An analysis of channel stability of the Red River from Shreveport, La to Index, Ar" Unpublished manuscript, 91 p.

Reid, J.B. (1984) "Artificially induced concave bank deposition as a means of floodplain erosion control" In, River Meandering, Proceedings of the Conference on Rivers '83, New Orleans, 1983, ASCE New York, ISBN 0-87262-393-9, pp 295-305.

Thorne, C.R. (1982) "Processes and mechanisms of bank erosion" In, Gravel-Bed Rivers, Hey, Bathurst and Thorne (Eds), Wileys, Chichester, UK, pp 227-271.

Thorne, C.R. (1988) "Analysis of bank stability in the DEC watersheds, Mississippi", Final report to the US Army European Research Office, London, England, under contract No. UA45-87-C-0021, 40 p.

Thorne, C.R. and Osman, M.A. (1988) "Riverbank stability analysis: Part II Applications", Journal of Hydraulic Engineering, ASCE, Vol 114, No.2, pp 151-172.

Veatch, A.C. (1906) "Geology of the underground water resources of northern Louisiana and southern Arkansas" US Geological Survey Professional Paper 46, 394 p.

Water Engineering & Technology (1987a) "Geomorphic and hydraulic analysis of the Red River from Shreveport, Louisiana to Denison Dam, Texas" Report to Vicksburg District, Corps of Engineers, under contract number DACW38-86-D-0062, August 1987, 207 p.

Water Engineering & Technology (1987b) "Investigation of erosion and flood control alternatives for Batapan Bogue Watershed" Report to Vicksburg District, Corps of Engineers, 96 p.

Yu, Bofu and Wolman, M.G. (1986) "Bank erosion and related washload transport on the Lower Red River, Louisiana" Third International Symposium on River *Sedimentation, Jackson, Mississippi*, March 1986, pp 1277-1285.