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BANK FAILURE AND EROSION ON THE OHIO RIVER

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ABSTRACT

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River bank erosion has been the focus of recent concern surrounding construction and operation of navigation dams along the Ohio River. Such factors as navigation pool levels, pool fluctuations, and towboat traffic have been alleged to be the cause of severe erosion of Ohio River banks. In this paper available information on Ohio River bank erosion is examined from an historical perspective and from the perspective of recent comprehensive investigations. Historical illustrations, photographs, and published reports indicate a history of significant bank erosion for more than 150 years on the Ohio River. Results of field bank condition reconnaissance studies suggest that construction of navigation dams on the Ohio River has not significantly accelerated or intensified bank erosion. Analysis of erosional mechanisms indicates that bank failure and erosion on the Ohio River are complex and episodic phenomena; however, the principal erosional mechanisms appear to be bank material removal by current tractive forces during flood events and internal erosion of bank materials by bank discharge following floods. It is concluded that waves generated by tow and recreational vessels have little impact on bank stability, but land use changes may affect slope stability and bank erosion.

INTRODUCTION

During the period 1970—1980, considerable attention has been directed toward the failure and erosion of banks and slopes along the Ohio River. The river is important to the commerce of the Midwest; millions of tons of raw materials and refined or manufactured products are transported annually along the Ohio River navigation system from Pittsburgh, Pennsylvania to Cairo, Illinois where the Ohio joins the Mississippi. These movements by tows are made possible by a series of locks and dams which retain ninefoot minimum depth pools.

Statements have been made by large numbers of riparian landowners along the Ohio River that bank failures and erosion have been caused and/or accelerated by the existence and operation of navigation-aid structures. Complaints also refer to Ohio River towboat-barge traffic on the waterway as causing prop turbulence and wave-related erosion; this erosion allegedly has been increasing with increases in vessel displacement and traffic.

Because of concern about failure and erosion of the banks of the Ohio River and because of a responsibility for maintaining and operating the navigation lock-and-dam system, Corps of Engineers staff and consultants monitored and evaluated bank failure and erosion on the Ohio River. These studies included, as a first step, a literature review to define the historical extent of Ohio River bank failures and erosion and to determine if present bank conditions are similar to those encountered in the past.

The Ohio River drainage basin lies within several physiographic regions, and changes character greatly between Pittsburgh and Cairo. Navigation dams at 21 locations along the river also define "retained-pool" reaches of the stream. Also, bank locations and river reaches can be referenced to river morphology; i.e., outside of bend, inside of bend, straight reach. A second portion of the total investigation was intended to determine the time of occurrence and the extent of bank failure and erosion, and the extent of transport and deposition of sediments, through an examination of resultant topography; a search was done to define any relations between these phenomena and physiographic province, pool retention and use, and river morphology.

A third aspect of the investigation was a review of the mechanisms by which river regimen is defined. Well-known mechanisms of erosion were reviewed. Reach-of-river and site-specific data regarding bank failure and erosion, obtained during initial phases of the study, were analyzed to identify operative mechanisms. Valley, floodplain, riverbank and channel topography were mapped and evaluated to delineate features which are characteristic of failure and erosion sequences. Direct detailed examination of bank conditions was combined with monitoring of vessel waves, climatological conditions and bank system responses at a number of sites.

Several aspects of these studies will be described in this paper, and evaluations and conclusions will be given.

HISTORICAL PERSPECTIVE

A site where bank failure and erosion or removal of debris has occurred during the period of these studies from late 1976 to 1980 is shown in Fig.1. It is not correct to consider any one site "typical" of conditions along the Ohio River because the banks are variable in sequence and character of the soils, in geometry and location relative to the channel and thalweg of the stream, in topography and drainage conditions immediately landward of the banks and along the valley slopes, in the use of the land adjacent to the banks and within the floodplain, and in many other factors. However, many of the bank characteristics shown in Fig.1 are to be seen at many locations along the entire Ohio River. An upper, near-vertical portion of the bank, including soils with significant apparent cohesion, was found. Thin layers of granular soils underlie the cohesive soils. Between the water's edge and the thin basal lenses of granular soil, cohesive soil debris fallen from the upper bank zones has accumulated. Removal of the thin granular layers undercuts the upper cohesive soils, which then develop tension cracks; eventually slabs of material fall off

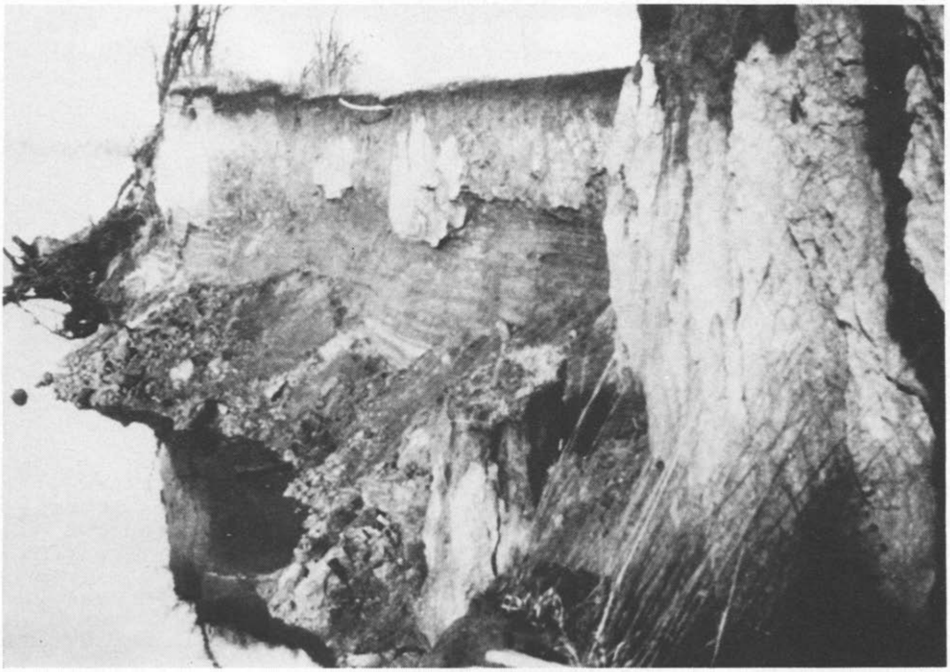

Fig.1. Left descending bank, Ohio River, 448 km (278 miles) downstream from Pittsburgh, 13 December 1977.

the bank face. Similar conditions are shown in Fig.2 for a site on the lower Ohio River.

The bank failure and erosion configurations shown in Fig.1 have historical relevance and are similar to bank conditions along much of the Ohio River and tributary streams at the present time. A search was conducted in public archives, agency files, and private collections, for photographs and other information on Ohio River bank conditions, particularly erosion thereof, from the time that the Ohio River Valley was first settled, to the present. Paintings and illustrations were found which depicted bank geometries as early as 1786. Numerous references to bank failure and erosion on the Ohio River as early as 1820 were found in the literature. Many historical photographs showed bare, apparently failed and eroded banks, much like those in Figs.1 and 2. Many of these photographs were taken prior to the construction of Ohio River navigation dams, with water levels in the photographs, in many instances, well below those maintained by the current system of dams. These historical photographs often show gently sloping lower bank areas at low-flow conditions, below the kind of bank conditions shown in Figs.1 and 2. A great number of paintings and illustrations of referenced locations were found showing similar conditions.

These historical photographs and illustrations are significant in that they show bank conditions before navigation dams had been built on the Ohio River, and the appearances of the banks in these illustrations are similar to the

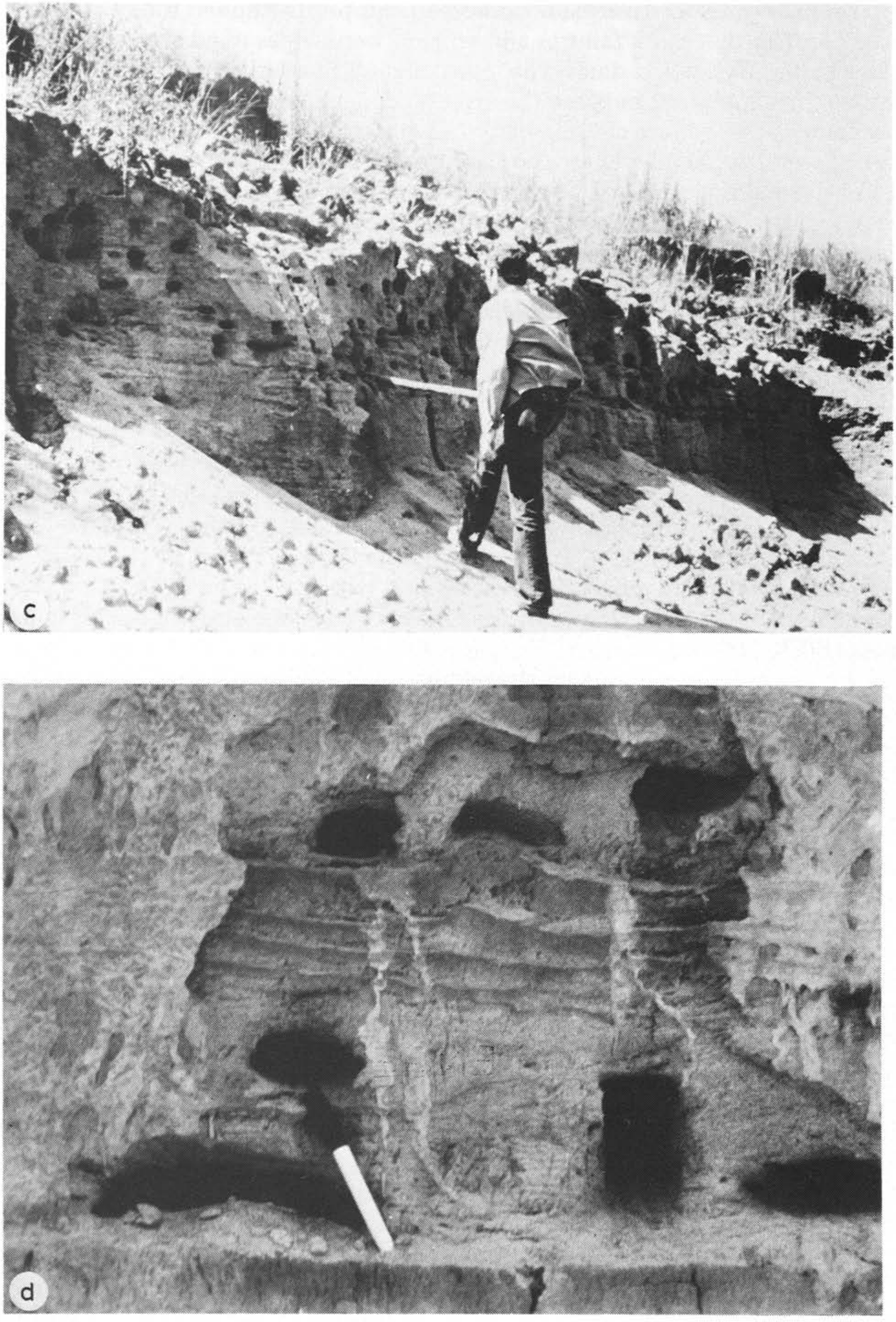

Fig.2. Left descending bank, Ohio River, 1320 km (820 miles) downstream from Pittsburgh, August 1978.

appearances of Ohio River banks observed and photographed today. These facts confirm that bank failures and erosion were widespread along the Ohio River before navigation dams were constructed. Similarities in appearance of banks (then and now) indicate the effects of mechanisms (or combinations of mechanisms) which are causing bank failures and erosion today. Furthermore, bare apparently failed and eroded bank reaches above sloping bank areas now below normal pool levels (but previously exposed at low water) indicate that bank failures and erosion historically have occurred at these high-water-defined elevations as well as elsewhere within the channel, during and after flood events.

Numerous references to Ohio River bank failures and erosion were reviewed in 18th and 19th centuries lay and technical literature. George Washington travelled to the Kanawha River mouth in 1770 to survey land for the Ohio Company and reported bank failures and erosion, and drift and snags in the Ohio River. Charles Dickens in 1842 noted failures and erosion of Ohio River banks he observed from the deck of a steamboat which took him from Pittsburgh to St. Louis. Reports to the Chief of Engineers, regarding the Ohio River before and after the Civil War, frequently refer to storm- and flood-related failures and erosion, and damage to facilities adjacent to the river.

In the first official report on bank failures and erosion, in 1852, Charles Ellet, Jr. stated that the banks of the Ohio were broken and lined with fallen trees (Ellet, 1853). In a later report Roberts (1871) stated that every tree "...on ground not over 60 feet above low water, is naturally a prospective snag", and "... the river even when within ordinary limits, is continually undermining portions of the banks, causing acres of bottomland to cave-in, bringing the tree stumps, and brushwood into the river in a wholesale manner."

In recounting his adventures during a solo voyage down the Ohio and Mississippi rivers to the Gulf of Mexico in 1878, Bishop (1879) described conditions along the Ohio: "The soft shores of alluvium were constantly caving and falling into the river bringing down tons of earth and tall forest trees." Reports by local historians describe widespread erosion damage. For example, the town of Boston, Indiana "... flourished chiefly about the time of the Civil War. It has 68 inhabitants, three stores, two churches, a school, a blacksmith shop, a carding machine, and 20 dwellings" (Bulleit, 1906). By 1911 it was noted that "... a cut in the river has washed the town away until nothing remains at this time" (Roose, 1911).

Bank failure and erosion at specific sites was documented. For example, the Illinois bank of the Ohio River between Mound City and Cairo (between 1560 and 1570 km (976 and 981 miles) downstream from Pittsburgh) receded about 43 m (140 ft.) between 1810 and 1880. Between 1883 and 1889, the bank recession was about 90 m (300 ft.), and more than 40 m (130 ft.) of bank recession occurred between 1889 and 1897. The episodic nature of bank recession is indicated by the fact that more than 30 m (100 ft.) of bank recession occurred during 1897—1899. Erosion at this site was ascribed to washing out of a fine sand layer beneath cohesive upper soil layers during and after periods of high water. In a letter dated December 7, 1903 (contained in a

1904 Report to the Chief of Engineers), Col. G.J. Lydecker, the engineer assigned to investigate this site, stated: "Although this recession of banks is quite extensive, it is hardly any more so than at many other places along the Ohio River above Mound City. The Ohio River has already hundreds of miles of caving banks . . ."

More recently, the 1937 flood (the greatest in recorded history on the Ohio River) caused extensive and severe bank erosion. For example, at Gallipolis, Ohio approximately 450 km (280 miles) downstream from Pittsburgh, this flood crested about 2 m above the average elevation of the river bank and inundated much of the town. In a letter to Congressman Thomas A. Jenkins, dated May 11, 1937, Major General E.M. Markham, Chief of Engineers, described the effects of the flood: ". . . severe erosion occurred over a considerable portion of the Gallipolis waterfront as a result of the flood of this year. The slides which occurred at that time have left the banks standing nearly vertical in a number of places and further caving may be anticipated . . ."

This reference is important since many allegations regarding erosion at the Gallipolis site have attributed erosion to the influence of the Gallipolis Lock and Dam near the city. However, the dam was not completed until after the flood and erosion described above. Continuing episodes of bank failure have been noted at this site after periods of high water in 1948, 1952, 1956, 1958, 1964, etc.

In responding to complaints by landowners that erosion has been accelerated by the construction of the Cannelton Dam 1155 km (721 miles) downstream from Pittsburgh and the Meldahl Dam 598 km (436 miles) downstream from Pittsburgh, extensive investigations were conducted at 22 sites. Included in this investigation was the interpretation of floodplain changes in topography, land use, vegetative cover and cultural features. This analysis used airphotos taken from 1930 to 1977. Results indicated bank top recession and sediment deposition were occurring during this period, with significant changes noted after periods of floods and above-average precipitation. Claims by landowners stated that erosion had not been significant at the 22 studied sites until the construction of the Cannelton and Meldahl Dams in 1971 and 1965, respectively.

In summary, historical photographs and illustrations, reports in lay and technical literature, and aerial photographs contained conclusive evidence that bank failure and erosion has been occurring along the Ohio River for at least 150 years, with most significant changes during and after storms and periods of flooding.

GEOGRAPHIC PERSPECTIVE

Bank failure and erosion conditions evaluated in these studies also were examined to better define persistent locations of bank failure and recession. Landowners claimed that increases in retained "normal pool" river elevations had increased or intensified failures and erosion. The dams built to facilitate navigation retain "pools" which at slack water have minimum depths sufficient to permit navigation by vessels drawing 2.75 m (9 ft) of water. A system of 51 low-lift wicket-type dams had been completed by 1929; higher, gated dams equipped with larger locks have been constructed more recently. At the present time (1981), 21 dams are in full operation on the Ohio River, with a new dam and locks being installed at Smithland, Kentucky, 1478 km (918 miles) downstream from Pittsburgh. Existing dams are listed in Table I.

With the recent construction of larger dams and locks, retained water levels were raised in some areas. The new Cannelton Dam, for example, raised normal pool water level 7.6 m (25 ft.) above the levels maintained by old Dam 46, 4.9 m (16 ft.) above the levels maintained by old Dam 45 and 2.8 m (9 ft.) above the levels maintained by old Dam 44, without change to the slackwater pool elevations maintained by old Dam 43 (see Fig.3). Similar situations existed for all the newer higher dams. This type of situation provided a means to test the allegations that raising the river elevations had accelerated or intensified bank erosion. If these allegations were correct, the river banks within the reaches where pool raises were greatest should exhibit more widespread and severe failures and erosion than the banks in portions of the stream where pool raises were less, or where no change occurred as in the case of the Dam 43

TABLE I

Ohio River navigation dams

Structure	Distance downstream from Pittsburgh (km)	(miles)	Pool length (km)	(miles)
Emsworth	10.0	(6.2)	10.0	(6.2)
Dashields	21.4	(13.3)	11.4	(7.1)
Montgomery Island	51.0	(31.7)	29.6	(18.4)
New Cumberland	87.5	(54.4)	36.5	(22.7)
Pike Island	135.4	(84.2)	47.9	(29.8)
Hannibal	203.3	(126.4)	67.9	(42.2)
Willow Island	260.1	(161.7)	56.8	(35.3)
Belleville	328.0	(203.9)	67.9	(42.2)
Racine	382.1	(237.5)	54.1	(33.6)
Gallipolis	449.2	(279.2)	67.1	(41.7)
Greenup	548.7	(341.0)	99.5	(61.8)
Meldahl	701.9	(436.2)	153.2	(95.2)
Markland	855.3	(531.5)	153.4	(95.3)
McAlpine	976.5	(606.8)	121.2	(75.3)
Cannelton	1159.8	(720.7)	183.3	(113.9)
Newburgh	1249.0	(776.1)	89.2	(55.4)
Uniontown	1361.5	(846.0)	112.5	(69.9)
Dam 50	1411.1	(876.8)	49.6	(30.8)
Dam 51	1453.4	(903.1)	42.3	(26.3)
Dam 52	1511.0	(938.9)	57.6	(35.8)
Dam 53	1549.1	(962.6)	38.1	(23.7)
(Mouth)	1579.5	(981.5)	30.4	(18.9)

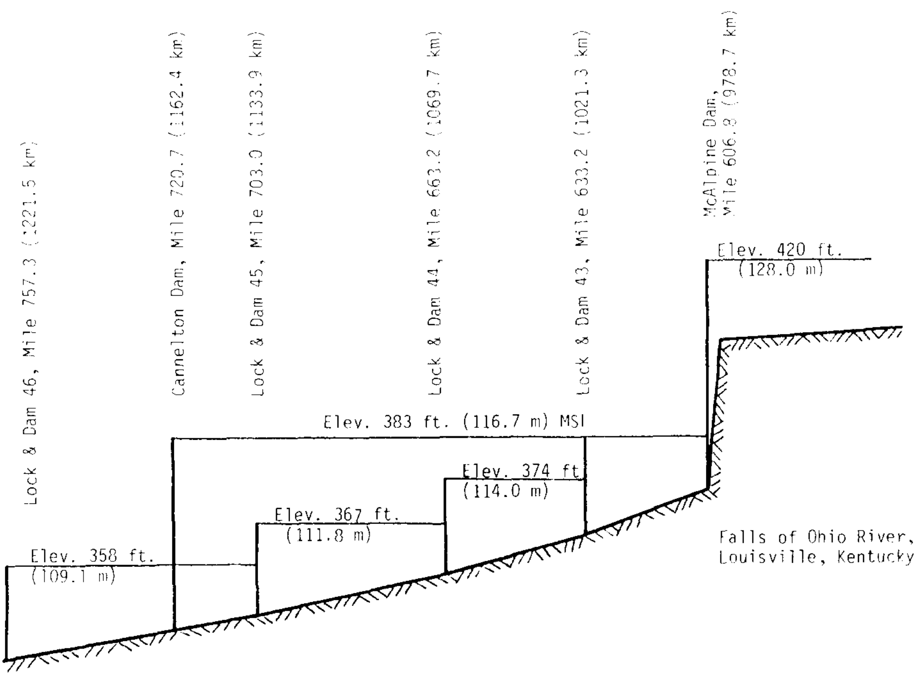

Fig.3. Diagram showing replacement of old Ohio River Dams 43, 44, and 45 by Cannelton Dam.

pool. To evaluate the hypothesis that pool raise has accelerated or intensified bank failures and erosion, reconnaissance and mapping of river island, embayment and bank areas was conducted. The mapping program conducted on the Ohio River is described in Table II.

Examination of the banks was accomplished from motor vessels operating near the bank (usually within 15 m) and from low-altitude helicopter overflights. Also, in December 1978, the Kentucky River banks near Frankfort, Kentucky were mapped after periods of record high water (on the Kentucky River). In May 1979, banks of the Kanawha River, another Ohio River tributary, were mapped, to define changes produced by storm and flood events which had occurred in winter-spring 1978—79. During November 1979, the banks of the Monongahela River were mapped and photographed. During these efforts, the authors mapped and evaluated over 8,100 km (5,500 miles) of Ohio River banks, with some reaches of bank being examined more than once. Additionally, more than 840 km (520 miles) of banks on Ohio River tributaries were investigated.

During these field investigation efforts, monitoring was conducted at specific locations. Mapping was accomplished by means of simple codes and references to slopes to indicate the appearance of the river banks. For example, if vegetation was found to the water's edge along a particular stretch of bank, on a map that reach of bank was colored green. Areas of colluvial armoring by soil and rock fragments were colored blue, as were rock outcrops. Bank areas

TABLE II

Ohio River mapping program

Dates	Reach mapped	Pools included
June—August, 1977	ORM 341.0 to 436.2 ORM 606.8 to 720.7	Meldahl Cannelton
December, 1977	ORM 203.9 to 341.0	Racine, Gallipolis and Greenup
May, 1978	ORM 203.9 to 341.0	Racine, Gallipolis and Greenup
July—August, 1978	ORM 0.0 to 981.5	All pools
December, 1978	ORM 606.8 to 720.7	Cannelton
December, 1978	100 sites between ORM 126.4 and 436.2	Willow Island, Belleville, Racine, Gallipolis, Greenup, and Meldahl
May, 1979	ORM 341.0 to 436.2 ORM 846.0 to 918.5	Meldahl Smithland (under construction)
June—July, 1979	ORM 126.4 to 203.9	Willow Island & Belleville
October, 1979	ORM 846.0 to 918.5	Smithland (under construction)

affected by artificial structures (fills, docks, jetties, etc.) were delineated on the maps in black. If natural alluvial or colluvial bank soils were bare and were apparently failed and eroded along a reach of bank, that map area was colored either yellow or red. If the bare areas were 1.2 m (4 ft.) or less in height, the bank reach was colored yellow; areas where higher bare banks were found were colored red on the map base. Notes on bank geometry, height of bare banks (if more than 3 m), adjacent land use, types and shapes of artificial structures and other physical conditions on the banks (slumpage, debris falls, slabbing, seepage, active erosion, etc.) were posted on the map base. These general mapping efforts were conducted to test the validity of many of the simple hypotheses advanced to explain bank failure and erosion causes and effects. Further evaluations of bank conditions were made possible by these reconnaissance efforts, also, since photographs of the banks were made at intervals of approximately 0.16 km (0.1 mile), and approximately 50,000 referenced 35-mm slides of bank conditions have been assembled.

Data shown in Fig.4 and Table III, indicate the evaluations obtained during examination of the 1580-km (981-mile) reach of the Ohio River in July—August 1978. These data do not fully describe the complex mechanism interrelationships which trigger bank failure and erosion. Rather, these reconnaissance data were used to evaluate hypotheses *suggested by others* to explain mechanisms of bank erosion. Thus, if pool raise as a result of construction of new dams had produced significant additional bank erosion, very recently

TABLE III

Results of 1978 reconnaissance

Pool	Age (yrs.)	% "Eroded"	% Vegt'd	Traffic metric tons 1977
Emsworth	40	0	25.0	21.7
Dashields	49	0	64.3	22.1
Montgomery Is.	42	13.9	33.3	20.5
New Cumberland	15	23.9	30.4	22.9
Pike Island	13	28.3	21.7	25.9
Hannibal	3	31.0	19.1	28.5
Willow Island	3	50.0	25.0	30.4
Belleville	10	51.2	21.4	31.0
Racine	7	59.1	22.7	32.4
Gallipolis	41	60.7	17.9	37.7
Greenup	16	53.2	21.0	35.0
Meldahl	14	54.2	28.4	32.6
Markland	16	36.8	31.6	
McAlpine	50	40.1	27.0	40.5
Cannelton	4	55.7	25.9	40.5
Newburgh	4	46.4	41.8	43.0
Uniontown	7	45.0	39.3	44.8
Dam 50	50	61.3	24.2	49.6
Dam 51	49	44.2	26.9	50.5
Dam 52	50	45.8	43.1	56.8
Dam 53	50	8.7	87.0	49.8

Percentages are based on total length of banks in a pool; "Eroded" = steep banks bare of vegetation; Vegt'd = banks covered with vegetation to the water's edge.

retained pools could be expected to show less severe and widespread erosion than older pools. However, no such correlation between age of pool and apparent severity of erosion could be found (see Fig.5). If pool raise were a significant causative factor in bank erosion, a correlation could be anticipated between magnitude of pool raise (from old dam slackwater pool to new dam slackwater pool) and extent and severity of bank failure and erosion; no such correlation was found (see Fig.6).

The navigation dams on the Ohio River are operated only to retain pools for navigation use; flow rates are determined at the dam structures and are regulated there. Thus, the water levels in the upstream reaches of navigation pools fluctuate somewhat more frequently, during low to moderate flows, than do water levels immediately upstream from the dams. These fluctuations, however, are not as great as those which occurred prior to construction of navigation dams on the river. With increasing flow, more gates in the dams are opened (or more wickets are lowered) to maintain pool conditions, until a

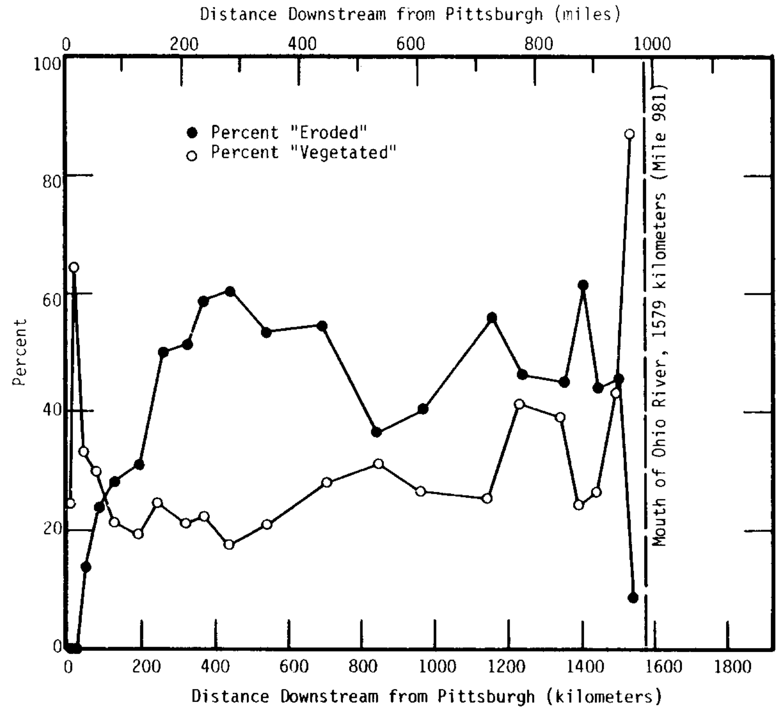

Fig.4. Bank conditions in Ohio River navigation dam pools versus distance downstream from Pittsburgh, July—August 1978.

condition is reached at which the dams no longer significantly impede flow. This open-river condition occurs well below flood stage, during conditions referred to as "excessive flow" conditions. Water level fluctuations in the upstream portions of the navigation pools have been referenced by a number of individuals as causing significant bank erosion within the upstream reaches of the pools. To test this hypothesis, reconnaissance trips were conducted to obtain data on the extent and severity of bank erosion in the upstream 30% of each pool as compared with conditions in the remaining 70% of each pool. No trends were apparent in the data (see Fig.7). In some pools, erosion was more widespread and severe in upstream portions, while the reverse condition was true in other pools, and in still other pools erosion appeared to be rather uniform throughout the entire lengths of the pools. *Bank failure and erosion was found to be a function of bank materials, topography, land use, river morphology and weather cycles.*

Some individuals have assigned significant bank erosion on the Ohio River to the effects of waves generated by passing vessels. A study of tow- and recreation-vessel waves was conducted by personnel of the Huntington District, Corps of Engineers during 1974. A more extensive study was made in 1978 as part of an assessment of the potential environmental impacts of traffic increases expected from improvements in the lock chambers of the Gallipolis Locks and Dam. Waves were monitored at several sites during the

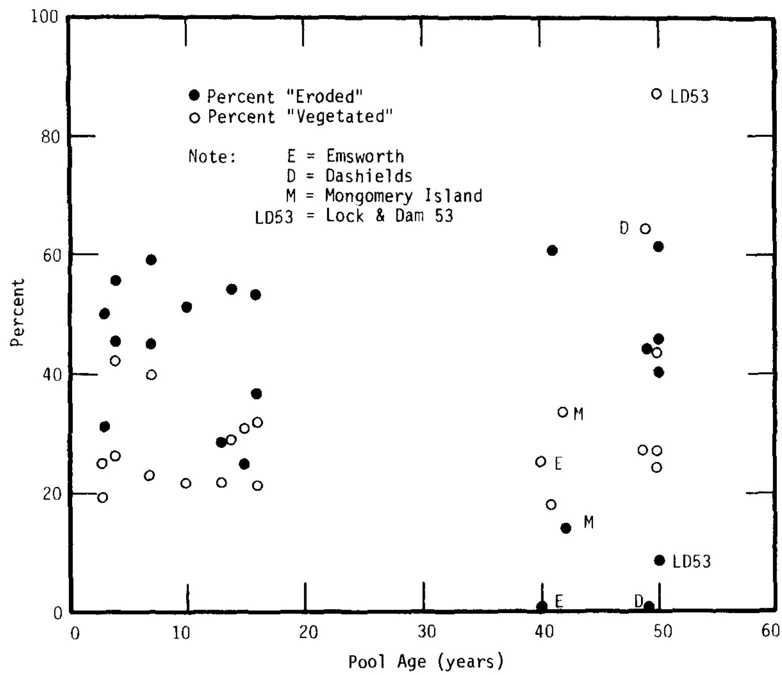

Fig.5. Bank conditions in Ohio River navigation dam pools versus pool age, July—August 1978.

passage of more than 200 commercial tows within the sailing line in the river. The maximum recorded wave height was 1.0 m (3.3 ft.). During the monitoring period, approximately ten tows per day passed the monitor sites.

The wave data and observations made during numerous reconnaissance trips indicate that wave-related erosion is not significant in comparison to storm- and flood-related bank failures and erosion. On the other hand, it was noted that prop wash and direct impact from motor vessels (e.g., temporary moorings) can significantly alter bank areas. Also, in the Ohio River system, islands were found on which banks near the designated channel areas (thus potentially most subject to vessel waves) were vegetated and apparently stable, while the opposite banks of these islands (remote from potential traffic effects) were bare and apparently failed and eroded.

Apparent severity of erosion is shown as a function of traffic volume in Fig.8. In this figure there appears to be an increase in erosion with increase in traffic volume, up to a volume of about 30 million tons per year. However, this relation does not suggest a significant correlation between traffic volume and erosion because of the following circumstances.

(a) In the pools where traffic volume is less than about 30 million tons per year (Emsworth, Dashields, Montgomery Island, New Cumberland, and Pike Island — between Pittsburgh and 135 km (84 miles) downstream) a very significant part of the banks (52% on the average) is either protected by artificial structures or colluvial/rock armoring and thus is not susceptible to erosion.

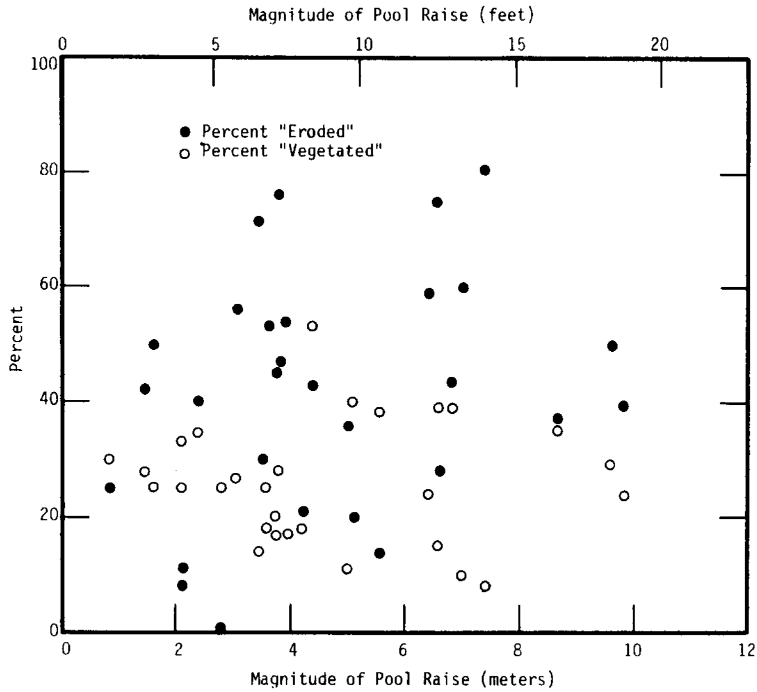

Fig.6. Bank conditions in Ohio River navigation dam pools versus magnitude of pool raise, July—August 1978.

(b) There is no increase in apparent severity of erosion with increase in traffic level above 30 million tons per year up to 57 million tons per year.

(c) There is a trend of increase in percent "vegetated" with increase in traffic volume above 30 million tons per year.

(d) The far upstream portion of the stream where traffic volume is less than 30 million tons per year, is less than 10% of the length of the entire river.

It must be mentioned also that the data in Fig.8 reflect the fact that the Dam 53 pool is subject to backwater conditions from the Mississippi River and during the reconnaissance of that reach, near normal pool conditions were not encountered.

EROSION MECHANISMS

Data obtained during field reconnaissance showed a seasonality of erosion, and unexpected results related to the location and time-occurrence of bank failure and erosion. Apparently eroded banks were noted as frequently on the insides of river bends as on the outsides of bends. Even though the thalweg of a sinuous stream tends to straighten during periods of high discharge and thus to attack (by tractive forces) the insides of bends, current-related erosion was expected to form bare banks primarily on the outsides of bends. Continuing monitoring of selected sites, as well as seasonal reconnaissance, indicated that

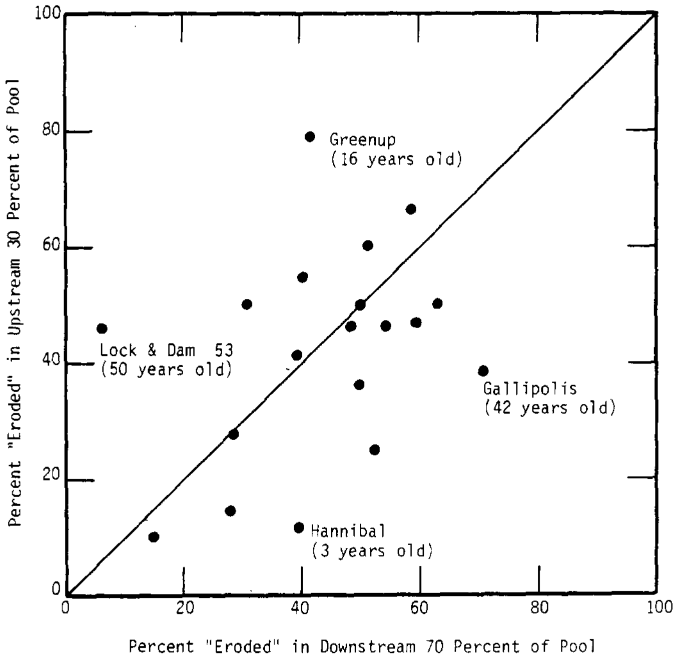

Fig.7. Bank conditions in upstream 30% of Ohio River navigation dam pools versus bank conditions in downstream 70% of pools, July—August 1978.

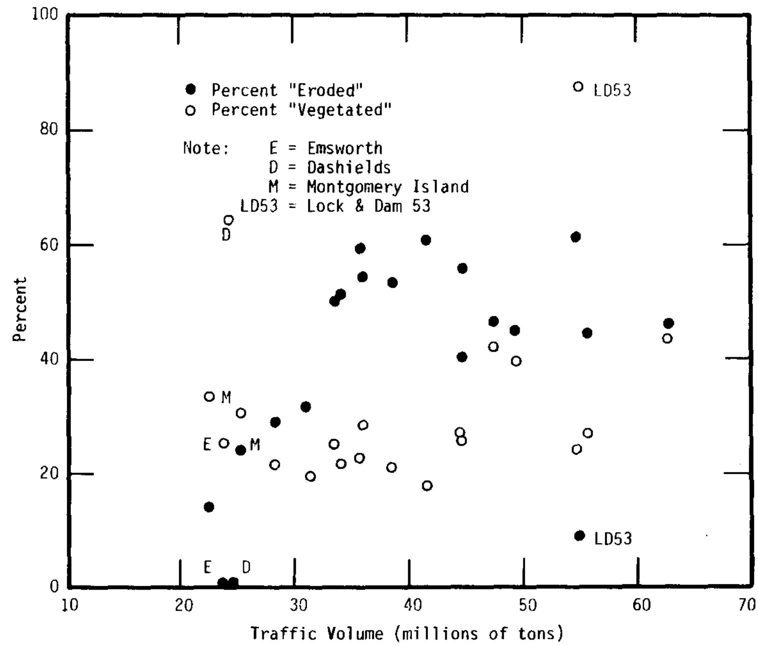

Fig.8. Bank conditions in Ohio River navigation dam pools versus traffic volume, July—August 1978.

bank and slope failures and erosion were occurring during periods when no significant flooding or high-water events occurred.

To better define these unexpected erosion conditions, detailed, site-specific investigations were conducted. These investigations included soil sampling, testing and analysis as well as evaluations of groundwater flow (on some sites, ranges of piezometers were installed). These site-specific studies included determination of stage-duration and stage-discharge relations (pre- and post-navigation dams), as well as monitoring of current velocities and waves generated by passing tows and recreation vessels and by winds. Series of aerial photographs (high-level vertical and low-level oblique) were obtained and analyzed. Finally, bank-level photographs were obtained during the entire period of study.

These detailed investigations disclosed landslides at several sites triggered by periods of greater-than-average precipitation. These landslides included colluvium (weathered rock and residual soil on slopes) and Pleistocene lake-bed deposits. At sites located on floodplain alluvium, erosion mechanisms were related to the character of the alluvial soils. As shown in Fig.1, the alluvial soils in the banks and terraces of the Ohio River occur as lenses and layers of varying thickness. Commonly, the texture of the lenses varies from sandy to silty or even clayey. The coarse-grained soil lenses are much more pervious (by several orders of magnitude) than the fine-grained soils. Thus, water flows preferentially in the sandy layers and lenses. When water flows out of the sandy layers it can remove these materials grain by grain, until more cohesive overlying layers are undermined and fail, as shown in Fig.1. The authors observed this process occurring at many sites. This internal erosion mechanism is most significant during periods of above-average annual precipitation such as the early 1970's, and could be more significant as a result of changes in drainage or land use which increase infiltration behind river banks. This mechanism was seen at a representative site in December 1977. Approximately 5 cm (2 inches) of rain had fallen on the site on 5—6 December; the temperature then had dropped and the last of the precipitation had fallen as a light dusting of snow. The river rose to flood crest on 9 December when the banks were frozen and stable. On 14 December 1977, temperatures rose above freezing. Soil-and-water was observed flowing out of the bank when the site was visited on 15 December. A close view of the flowing soil is shown in Fig.9.

Although this mechanism of erosion had been described long ago by other investigators (Thomas and Watt, 1918), the significance and areal extent of the mechanism had not been defined. This mechanism of erosion was noted by the authors within alluvial soils seasonally throughout the entire length of the Ohio River. Conditions on the left descending bank of the Ohio, 1320 km (820 miles) downstream from Pittsburgh, have been shown in Fig.2. The holes in the bank and the flow patterns in soil debris indicate the occurrence of this mechanism of "internal" erosion.

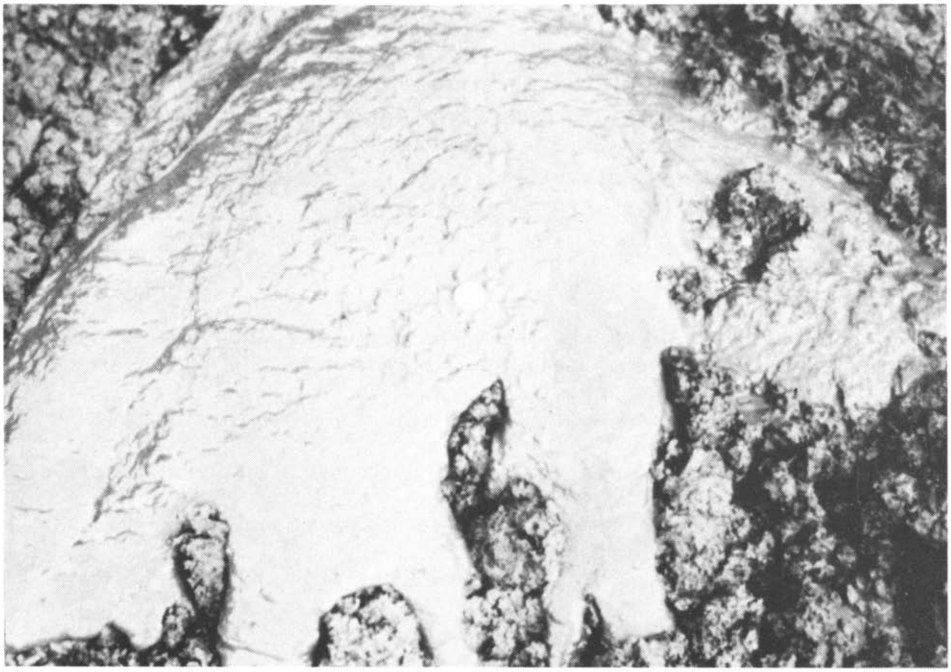

Fig.9. Soil and water flowing out of right descending bank, Ohio River, 662 km (411 miles) downstream from Pittsburgh, December 1977.

CONCLUSIONS

The investigations described in this paper have shown that:

(1) Bank failure and erosion on the Ohio River are complex, episodic and caused by an interplay, usually sequential, of causative factors.

(2) Current tractive forces during floods, and gravitational and internal water forces during recession of flood waters, are predominant causes of bank recession.

(3) Bank erosion has been recorded for more than 150 years on the Ohio River, as demonstrated by historic illustrations and photographs and published reports.

(4) Construction and operation of navigation dams has not significantly accelerated or intensified bank failures and erosion on the Ohio River.

(5) No significant correlation between traffic level and bank erosion was found, but prop turbulence and the direct impact of towboats operating approximate to river banks may have significant site-specific effects.

(6) Land use may affect slope failures and bank erosion, if water infiltrating behind river banks causes persistent seepage and internal erosion.

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