Repair of Scour Holes and Levees After the 1993 Flood

Mary P. Perlea
U.S. Army Corps of Engineers, Kansas City, Missouri

Robert L. Pearce
U.S. Army Corps of Engineers, Kansas City, Missouri

Kathleen E. Lust
U.S. Army Corps of Engineers, Kansas City, Missouri

Charles W. Detrick
U.S. Army Corps of Engineers, Kansas City, Missouri

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Mary P. Perlea
U.S. Army, Corps of Engineers
Kansas City District, USA

Kathleen E. Lust
U.S. Army, Corps of Engineers
Kansas City District, USA

Robert L. Pearce ,
U.S. Army, Corps of Engineers
Kansas City District, USA

Charles W. Detrick
U.S. Army, Corps of Engineers
Kansas City District, USA

ABSTRACT

The record high water during the summer of 1993 significantly impacted the flood control levee structures in the U.S. Army Corps of Engineers, Kansas City District. Scour holes in the levees and their foundations reached bedrock, up to 75 feet deep in some places, and extended up to 2,000 feet landward of the landside toe on lengths reaching 2,100 feet along selected levee embankments. Different methods used by the Corps of Engineers to repair the scoured levee embankment and foundation soils, their hydraulic impact on river stages, and the efficiency of different methods are presented. The methods discussed consist of: (1) backfill of the riverside scour holes; (2) backfill of the scour hole and reconstruction of the levee embankment to the original centerline; (3) realignment of levees landward of the scour holes; and (4) a grouted cut-off wall in a rockfill embankment and construction of a ring levee around the landside scour hole. The efficiency of different methods was evaluated by observation of the levee system during subsequent flood events.

KEYWORDS

Dredging, Grouting, Levee Repair, Riverbank Erosion, River Hydraulic, Scour Hole, Seepage, Stability, Underseepage, 1993 Flood

INTRODUCTION

The Missouri River basin is the largest of the 18 major water resource regions in the United States, embracing 513,000 square miles within the United States and 9,715 square miles in Canada. The Missouri River flows in a southeasterly direction 2,315 miles from its headwaters at Three Forks, Montana, to its confluence with the Mississippi River, near St. Louis, Missouri. The Kansas City District of the U.S. Army Corps of Engineers is responsible for the lower Missouri River basin from Rulo, Nebraska, at river mile 498.1 to the mouth at St. Louis, Missouri, a drainage area of 110,445 square miles. The Missouri River basin, as a whole, has an average annual precipitation of 20 inches, with the river flow heavily influenced by snowmelt runoff in the spring. The streams in the lower Missouri River basin generally have moderate to high flows during the spring and fall months, with relatively short duration high flows caused by summer storms or winter snowmelt.

Water resources in the Kansas City District have been extensively developed by the Corps of Engineers and the Bureau of Reclamation. The Kansas City District operates 18 multipurpose lake projects. The Bureau of Reclamation operates another 11 lake projects in the lower basin for flood storage and irrigation. Flows on the lower Missouri River are substantially affected by six main stem lake projects in the Omaha District, U.S. Army Corps of Engineers, which regulates the runoff from the upper Missouri River basin. Levees and/or channel improvement projects constructed by the Kansas City District provide flood protection for 51 locations. Of the 51 locations, 15 are levees constructed as part of Missouri River Levee System (MRLS); others are located on Missouri River tributaries. Some of the local protection projects have multiple units contributing flood protection at a single location.

The flood of 1993 affected a large portion of the north-central and midwest United States — the lower Missouri River basin and the Mississippi River above St. Louis. Many tributaries of these two rivers experienced record river stages in the spring as a result of unusual weather patterns persisting over a threemonth period. Total precipitation varied between July 1 and 26, ranging from 3.3 inches at Harlan County Lake, Nebraska, to 24.4 inches in Falls City, Pawnee City and Table Rock, Nebraska. Hydrologic and hydraulic effects of the runoffs from these events resulted in severe and widespread flooding throughout the lower Missouri River basin in Missouri, central and east Kansas, southeast Nebraska and south-central and southwest Iowa.

In 1993, the Missouri River's actual peak discharge of 755,000 cfs at Boonville, Missouri, exceeded the 500-year peak discharge of 700,000 cfs at the same location. The extent and duration of flooding caused many levees on the Missouri River to be overtopped, and the banks and channels of many rivers and streams to be severely eroded. Most of the Kansas City District projects were subject to conditions nearly equal to or exceeding their designs. One-hundred twenty-nine non-federal levees along the 535 miles of Missouri River controlled by Kansas City District applied for assistance for repairing damage, such as breaching, overtopping, wavewash, sidewash and topwash. Six of the Missouri River levee units constructed by the Kansas City District were overtopped, resulting in four being breached by erosion of the levee embankment and levee foundation. The design discharge and the peak discharge at these six levees are listed in Table 1.

Table 1. Missouri River Discharge during Flood of 1993

Levee Unit	Location	Design Discharge (cfs)	1993 Peak Discharge (cfs)
R-471/460	Elwood, KS	325000	335000
L-448/443	Halls, MO	325000	335000
L-408	Rushville, MO	270000	335000
L-400	Waldron, MO	348000	335000
L-246	Brunswick, MO	400000	755000
Lower Chariton	Glasgow, MO	476000	755000

Prior to overtopping, underseepage instability and sand boil activity developed at some locations. There is evidence that this activity may have contributed to the failures.

The rehabilitation methods of levee breaches and scour holes are discussed below. The hydraulic impact of landside realignment of the levee embankment is also discussed herein. The levees with the most damages due to scouring of the embankments and their foundations were the MRLS units L-246, L-400 and R-471/460, Lower Chariton Levee units and Cambridge Levee, a private levee between Glasgow and Salina, Missouri. The federal levees discussed were all designed as agricultural levees, although R-471/460 does provide protection to some urban developments.

METHODS OF LEVEE REHABILITATION

Methods of repairing breaches included levee reconstruction along the original alignment and/or set-back realignments around scour holes in conjunction with complete or partial backfilling of scour holes. In general, riverward realignments were rejected because of floodway boundary encroachment and the resultant adverse impact on future flood stages. The amount of the scour hole filled was based on underseepage characteristics of the embankment and its foundation, stability of embankment slopes, and the hydraulic impact of the remaining unfilled scour. Environmental, regulatory, and cost restrictions were also incorporated.

The levee rehabilitation program was conducted under Public Law (PL) 84-99 authority. Repair methods selected under this authority must be the least cost alternative with a benefit to cost ratio greater than unity unless the sponsor for the project elects to pay the difference. The program emphasis is to restore the pre-flood level of protection as expeditiously as possible. Consequently, in-depth analyses of failure modes are not done. Geotechnical and hydraulic analyses were performed to determine adequate technical solutions for repair. However, analyses were generally performed using existing subsurface data with minimal new investigations.

Underseepage calculations considered the original impervious blanket thickness versus different thicknesses proposed for reconstruction of the foundation stratification, to obtain a minimum acceptable factor of safety. The minimum gradient factor of safety considered in underseepage calculation was 1.3 at the landside levee toe and 1.1 at the toe of the underseepage berms (0.8 for underseepage berms longer than 200 feet on agricultural levees). A safety factor of 0.8 was allowed beyond 200 feet because some floodlighting is considered acceptable on agricultural levees compared to the amount of risk aversion that is practical, given the limitations of the analysis methods used and the variability level of foundation and blanket materials. If the construction of berms was not feasible, relief wells were designed to control the underseepage. Minimum safety factors utilized for stability analyses were 1.3 for steady state conditions and 1.2 for end of construction conditions. Hydraulic calculations determined the necessity of slope protection on portions of realigned levee embankment, using the original design flood event.

Backfill of Riverward Scour Holes

Scour holes that were created on the foreshore area riverward of the levee toe varied from 10 to 80 feet deep, which is to the top of bedrock in some cases. The scour hole lengths measured from 50 feet to 2,200 feet along the levee toe. The removal of material by scour at the levee toe threatened the stability of the embankment and compromised underseepage control of the levee. The most used method of restoring levees that were damaged in this manner was to backfill the scour area and reconstruct the levee slope. The backfill for scour holes consisted of granular material covered with impervious soil to restore the original impervious blanket. Granular material was obtained from dredging or from sand deposited on foreshore areas by overbank flows. Underseepage analysis determined the limits of backfill, the thickness of the impervious blanket, and the necessity of landward underseepage berms. Portions of scour holes extending beyond 200 feet of the riverside levee toe were not filled.

<u>Levee Unit L-400</u>. L-400 is located on the left bank between river miles 385 and 391.2, near Waldron, Missouri. The height of the levee varies between 12 and 20 feet. The levee was designed for a 100-year flood event with 2 feet of freeboard. During the 1993 flood, the levee was overtopped along the lower approximately 1,800 feet of its length causing breaches at three locations and erosions and scouring of the riverside levee slopes, foreshore and landward toe areas. The riverside scour hole cut through the pre-existing borrow area traverses, resulting in a scour approximately 200 feet wide and up to 35 feet deep that extended to within 50 feet of the riverward levee toe. The impervious blanket at this location consisted of lean clay approximately eight feet thick outside of borrow pits and five feet thick within borrow pits.

Two repair alternatives were analyzed. One was to construct a rockfill dike 100 feet from the levee centerline, having 1(V) on 1.5 (H) side slopes and a ten-foot wide crown. Granular material was proposed as backfill between the rockfill dike and levee slope. The upper five feet was to be constructed of compacted impervious material. A variation of this alternative was to replace the rockfill dike with granular material, constructing a platform to 160 feet from the levee toe that would be overlain with a five-foot thick layer of impervious material. A second alternative, selected as the most efficient, was to backfill the entire width of the scour hole with granular material on 1(V) on 100(H) slope and to reconstruct a three-foot thick impervious blanket on top of the sand backfill. Underseepage analysis required 140 feet wide underseepage berms along 350 feet of the landside toe. The repair of this scoured levee required 64,000 cy of cohesive material for the impervious blanket and the riverside levee slope, 157,000 cy of sand for the backfill of the scour hole, and an additional 3,000 cy of random material for the underseepage berm. Cross sections of the selected alternative are presented in Fig. 1.

<u>Backfill of Scour Holes and Reconstruction of Levee Embankments Along Original Alignments</u>

Most of the major damages produced by overtopping were breaches of the levee embankments and scouring of the levee foundation, foreshore and landward areas. The scour extendedin

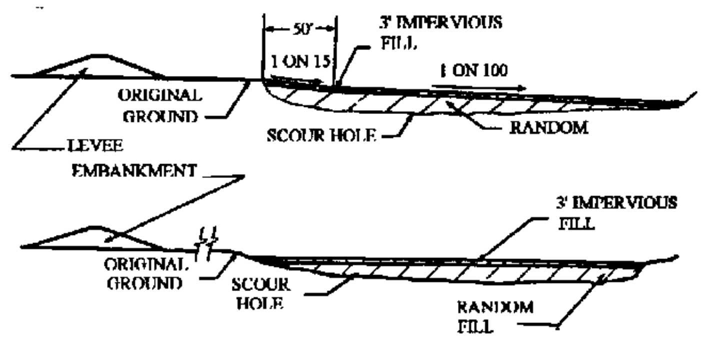

Fig. 1 MRLS L-400, Sta. 233+17 to 267+17. Complete backfill of riverbank scour hole.

some cases up to 2,000 feet landward from the levee centerline, breaching as much as 2,100 linear feet of levee embankment. Underseepage and stability anlyses determined the technical merit of different alternatives. In addition, recommended repairs had to meet environmental requirements. Subject to meeting the technical and environmental requirements, levees were reconstructed along original alignments where the costs could be economically justified or where levee sponsors elected to cover costs in excess of the most economical solution.

<u>L-246 Levee Unit</u>. The L-246 is located on the left bank of the Missouri River between river miles 239 and 250, near Brunswick, Missouri. Near the midpoint of the main stem portion, the levee ties back along both banks of Palmer Creek from its confluence with the Missouri River up to the Norfolk & Western Railroad. The levee extends upstream along the left bank of the Grand River and at the downstream end along the right bank of the Chariton River. The levee protects 31,000 acres of farmland and is about 24 miles long. The levee was designed for a 25-year flood event and was overtopped during the flood. As a result, 11 levee breaches occurred along the levee unit — most of them on the Missouri River, one on right bank of Palmer Creek tie back levee and one on the right bank of the lower Chariton River tie back levee.

A breach at Missouri River mile 240 on L-246 created a 400-foot long scour hole that extended 300 feet riverward and 75 feet landward of the levee centerline. The maximum depth of the scour was 40 feet. The selected alternative for repair was to backfill the scour hole and reconstruct the levee embankment to its original geometry. Underseepage analysis, followed by economical analysis, determined the optimum thickness of the reconstructed impervious blanket, considering different widths of landside berm. The plan view of the scour hole and the repaired cross section are shown in Fig. 2.

The repair required 4,500 cy of impervious material in the levee embankment, 24,500 cy of impervious material in the blanket, 23,600 cy of granular fill underneath the blanket, and 3,500 cy of random fill for the reconstruction of the existing underseepage berm.

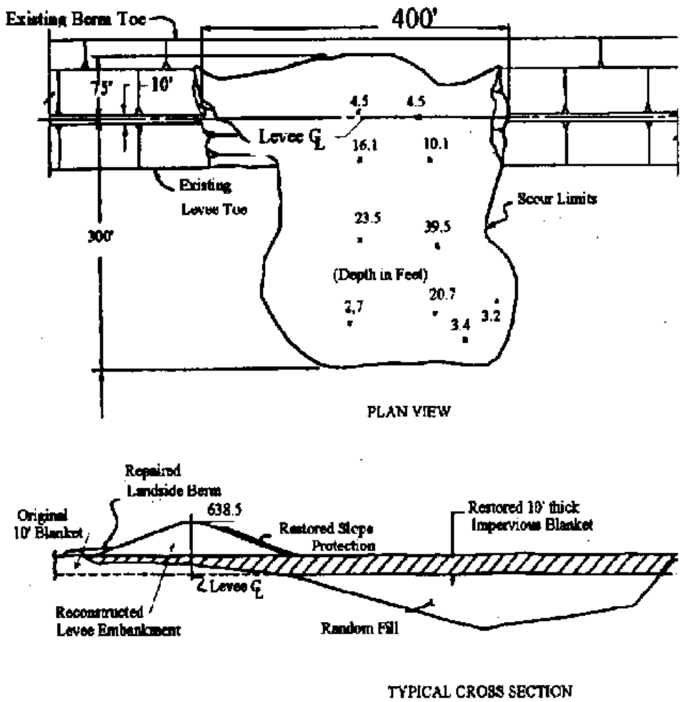

Fig. 2 MRLS L-246, Levee Breach Stations 674+20 to 678+20

<u>Lower Chariton River Levee Unit</u>. This levee extends approximately five miles along the left bank of the Lower Chariton River, then downstream along the Missouri River left bank between river miles 227.5 and 238.7 and then five miles upstream along the right bank of the Little Chariton River. The levee was designed for a 25-year flood event. The levee breached at two locations along the Missouri River main stem. The upstream levee breach removed 1,250 linear feet of levee and scoured the foundation to significant depths. The scour hole extended 1,400 feet landward of the centerline and 300 feet riverward the entire foreshore width. Soundings indicated scour hole depths of 60 feet on the riverside of the levee and 50 feet on the landside. Two alternatives were studied for repair: (1) realignment of the levee landward of the scour hole, and (2) reconstruction of the levee along its original alignment on a platform created by partial backfilling of the scour hole.

The landward realignment added about 5,400 linear feet to the original levee embankment. Due to the thinness of the impervious blanket and the shorten entrance condition for seepage (i.e., the proximity of the river to the embankment), the repair included limited filling of the scour riverward of the realignment and a long landside underseepage berm. This alternative also included a 500-foot long rockfill revetment along the landside edge of the scour hole for erosion protection.

A second alternative was to construct a platform of dredged river sand in the scour hole from dredged river sand and reconstruct the impervious blanket and levee embankment along its original alignment. This alternative, which was economically comparable with the levee realignment and preferred by the levee sponsor, was used for the rehabilitation. The platform was extended to the riverbank and 550 feet landward of the levee centerline. A rockfill dike was constructed at the riverbank between the upstream and downstream end of the scour hole. The rockfill dike has 1(V) on 1.5(H) side slopes and a five-foot wide crown. Sand dredged from the river was used for backfilling the scour hole behind the rockfill dike. Underseepage analysis determined the thickness of the impervious blanket constructed above the dredged sand platform and the width of the underseepage berm. The analysis indicated the need for a 140-foot wide landside berm and a blanket thickness of three feet. The blanket was constructed of silty clay from the nearby borrow areas. Random material used within the levee embankment and seepage berm consisted of the silty sand that was deposited by overbank flood flows. Seepage through the embankment was controlled with a five-foot thick impervious face on the riverside slope and a three-foot thick impervious cap on the levee crest. The riprap slope protection was reconstructed on the entire riverside slope of the levee. The alternative is shown in Fig. 3.

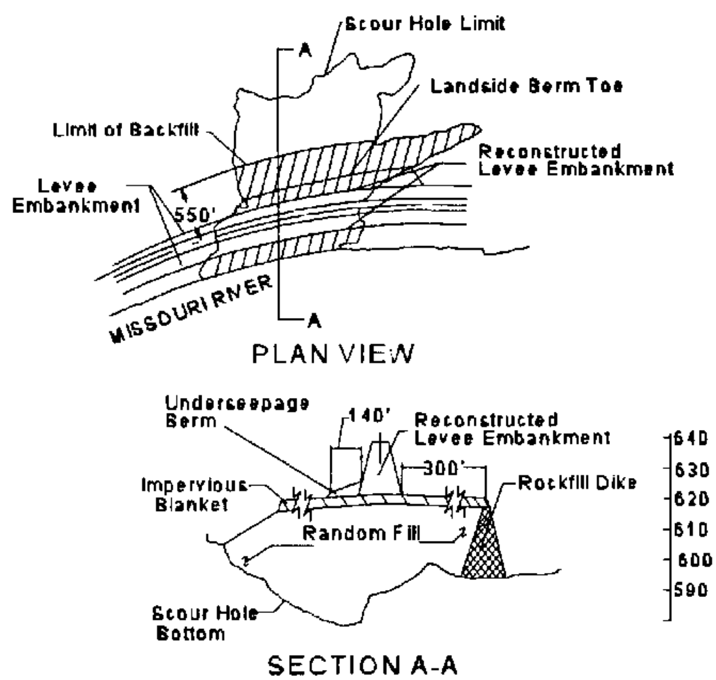

Fig. 3 Lower Chariton River Levee. Backfill of the Scour Hole and Reconstruction of the Levee at the Original Location

The repair required 8,000 cy of impervious fill and 25,000 cy of random material for reconstruction of the levee embankment and landside underseepage berm, 6,200 tons of riprap and 2,000 tons of bedding material to reconstruct the levee slope protection, 300 tons of aggregate surfacing for reconstruction of the levee crest road, 700,000 cy of dredged sand for backfilling the scour hole, 360,000 cy of impervious material for reconstruction of the impervious blanket on the top of the dredged sand, and approximately 8,000 tons of quarry run rock for construction of the riverside rock dike.

The rehabilitation of the levee was not completed prior to another flood in May 1995 that crested five feet below the design levee crest. At the time of the second flood, reconstruction of the levee embankment was eight feet short of its required 14 foot height along the 1,250 foot length of the breach repair. In order to prevent overtopping the contractor was directed to make an emergency closure of the gap with impervious material already placed as landside blanket. The contractor successfully completed the emergency closure to two feet above the design height in two days. However, three days later the sustained river stage four feet below the raised levee height resulted in piping developing at the landside levee toe. To prevent another breach of the levee, the contractor was directed under emergency operations to construct a forty-foot wide, five-foot thick rockfill toe over geotextile filter fabric at the toe of the landside slope. The rockfill consisted of 40,000 tons of quarry-run rock. Later the rockfill was extended another 500 feet along the levee toe. Three feet of material similar to the soil used in the underseepage berm was placed over the rockfill to prevent further piping during high river stages. Standard penetration tests in the uncontrolled levee fill that was placed during the emergency indicated a density less than the underlying six feet of controlled fill. However, stability analysis of the levee embankment (using low strength parameters corresponding to results from the Standard Penetration Tests) indicated a factor of safety greater than 1.3 for both riverside and landside slope. Consequently, the emergency fill was incorporated into the finished embankment.

Levee Unit R-471/460. This MRLS levee is located on the right bank of the Missouri River between river miles 441.7 and 456.6 across the river from St. Joseph, Missouri. The levee is 13.8 miles long with an average height of 14.8 feet and protects 11,000 agriculture acres and 2,300 urban acres including the city of Elwood, Kansas, the St. Joseph Municipal Airport, and the Missouri Air National Guard Base. The design elevation was established to protect against a 100-year flood event with a two-foot freeboard. During the flood of 1993, the levee was overtopped and the embankment eroded and breached at two locations. In addition to the loss of 1,100 feet of levee embankment at the upstream breach, the flood waters scoured the embankment foundation to depths up to 46 feet over a 26-acre area. Two alternatives were considered for repair of the breach: (1) construct a levee realignment landward of the scour hole, and (2) construct the levee to its original alignment. Although the realignment alternative proved to be less costly than the original alignment alternative, the levee sponsor paid the cost difference and the original alignment was selected.

The 5,595-foot long realignment added 455 linear feet to the original embankment length and included design underseepage berms of 300-foot or 450-foot widths, depending upon proximity to the unfilled portion of the scour hole. At the beginning and end of the realignment where it was more than 1000 feet from the unfilled scour hole, the original alignment berm type and size was used. Filling of the scour hole was extended 200 feet from the levee toe. A two-foot thick layer of quarry-run rockfill slope protection was included on the scour hole fill slope, vulnerable scour hole faces, and the levee transitions.

The selected alternative, constructed to the original alignment, is shown in plan view and cross section on Fig. 4.

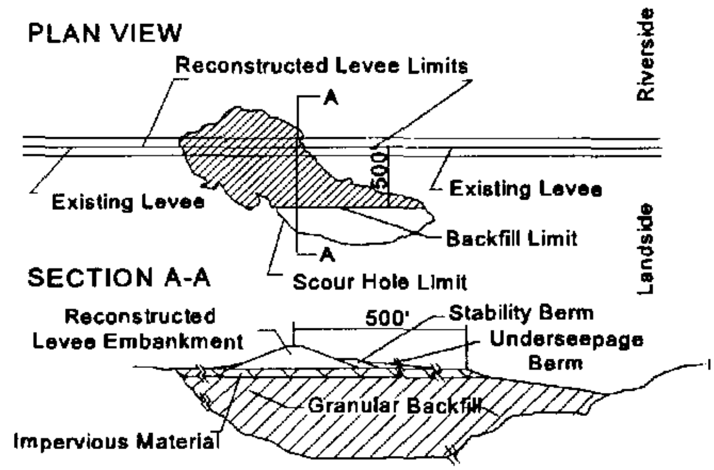

Fig. 4 R-471/460. Backfill of the Upstream Scour Hole and Reconstruction of the Levee at Original Alignment

The scour hole was filled from its riverward extent to a distance of 500 feet landward of the levee alignment's centerline to ensure an acceptable gradient factor of safety. Although it was acknowledged that partially filling the scour hole would increase the seepage quantity on the protected side of the levee, the increased seepage would flow into designated ponding areas. The scour hole fill consisted of 501,500 cy of Missouri River dredge sands and 128,300 cy of hillside loess to reconstruct to the original four-foot thick impervious blanket. The original 180-foot wide underseepage berm and the 45-foot wide combination stability and underseepage berm were reconstructed to their original limits.

Realignment of Levee Embankments Landside of Scour Holes

Levee Unit L-246. At river mile 250, L-246 sustained a series of breaches and scours along a 1,740-foot length of embankment. A scour hole at the upstream limit of the breach measured 340 feet long, up to 41 feet deep, and extended landward 250 feet and riverward 100 feet. At the downstream end of the breach a second 200-foot long scour hole with a maximum depth of 36 feet extended 175 feet riverward and 600 feet landward from the levee centerline. Two other shallow scour holes, approximately six and ten feet deep were present on either side of a remaining segment of the embankment. Various combinations of backfilling scour holes and reconstructing the embankment along the original alignment were studied. However, landward realignment was chosen as the most economical solution. The realignment began 1,220 feet upstream of the breached area and tied back into the existing levee approximately 1,850 feet downstream of the breached area. Because this realignment cut off a pre-existing bend in the original alignment, its length was 650 feet shorter. A plan view of the levee rehabilitation is shown in Fig. 5.

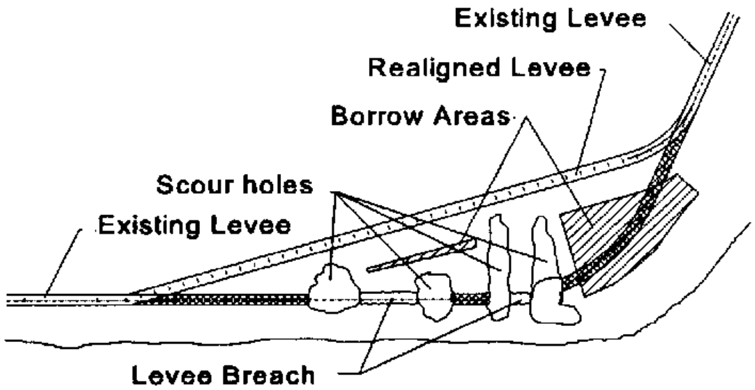

Fig. 5 MRLS L-246. First Levee Realignment Around the Scour Holes on the Upstream Breach.

Underseepage analysis determined the minimum setback distance of 125 feet from the landside edge of the scour hole. The realignment left approximately 45 acres of previously protected land on the riverside of the setback alignment. The riverside slope of the reconstructed levee was protected with a two-foot thick layer of quarry-run rockfill on the downstream 1,200-foot reach. Quarry-run rock was also placed on the landward bank of the scour hole for erosion control. Remnants of levee embankments riverward of the realignment were used as borrow material for the reconstruction. The repair required 30,000 cy of impervious material and 45,000 cy of random fill for construction of the realigned levee embankment.

Three additional levee breaches occurred on L-246 between stations 316+15 and 359+00. The first 450-foot wide breach was associated with numerous scours holes. One scour hole through a breach was a maximum of 50 feet deep and extended 400 feet riverward and 350 feet landward of the levee centerline. Another narrow scour hole, a maximum of 20 feet deep, was located 600 feet farther landward.

A second 300-foot wide breach approximately 3,000 feet downstream created a scour hole up to 42 feet deep and 400 feet wide. The scour hole associated with this breach extended from the riverbank 1,650 feet landward, where it narrowed to a width of approximately 250 feet. A third 1,050-foot wide breach occurred 300 feet farther downstream. At this location the scour hole through the breach was 41 feet deep and 400 feet wide and extended 300 feet riverward and 1,200 feet landward from the levee centerline. Numerous shallow erosions of the foreshore occurred between the riverward limit of the scour hole and the existing rockfill dike along the Missouri River channel. Backfilling of the three scour holes through the breaches and reconstruction of the embankment along the original alignment was studied. However, underseepage analysis indicated that backfilling a minimum of 500 feet from the landside levee toe would be necessary to ensure the safe performance of the levee foundation and to maintain underseepage quantities at acceptable levels. Consequently, levee realignment landward of the three breaches was chosen as the most economical solution. The realignment tied into the original levee embankment 4,300 feet upstream of the first breach and 2,300 feet downstream from the edge of the third breach. The realigned levee is 9,760 feet long and is constructed to the same height as the original levee. Based on underseepage analyses, the minimum setback of the realignment from the landward edge of the scour holes was 300 feet for the upstream hole and 125 feet for the two downstream holes. Rockfill slope protection was constructed at areas where higher velocities could occur as a result of the realignment. Approximately 125 acres of land between the original alignment and the realigned levee were left unprotected by the realignment. The portions of the original levee embankment between the upstream and downstream ends of the realignment were used as a borrow source for the realignment. Quantities required for the repair of the levee at this location included 100,000 cy of impervious soil and 230,000 cy of random fill. The plan view of the repair is shown in Fig. 6.

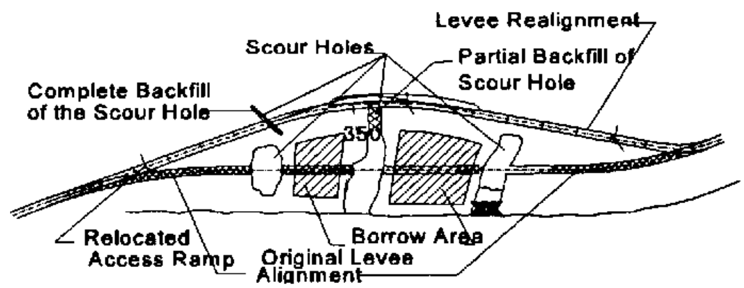

Fig. 6 MRLS L-246. Second Levee Realignment Around the Scour Holes.

Another 400-foot long breach of the L-246 embankment occurred on the downstream tie back along the lower Chariton River. The scour hole extends from the riverbank 400 feet landward with depths up to 45 feet. A levee realignment landward of the scour hole was chosen as the most economical alternative. The realignment distance from the original levee centerline was limited by a drainage structure 185 feet upstream of the scour hole. A rockfill toe was necessary on the upstream end of the scour hole to assure the minimum stability safety factor of 1.5 because of the realignment's proximity to the scour hole edge. Underseepage calculations required construction of a 340-foot landside underseepage berm along the entire realignment. Two relief wells were also required on both sides of the drainage ditch to the structure. The necessary quantities for repair of this reach were 18,000 cy of impervious material, 80,000 cy of random material, and 6,000 tons of rockfill. A plan view of the repair is shown in Fig. 7.

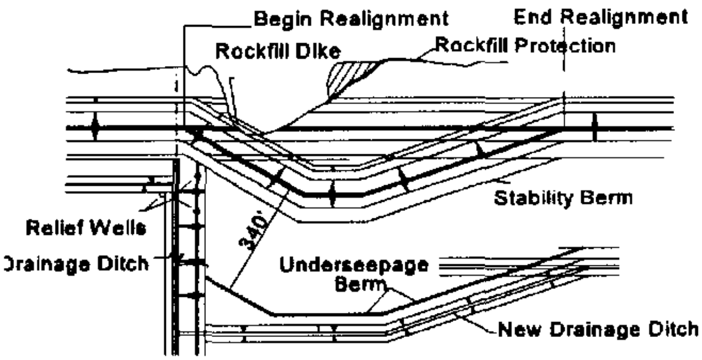

Fig. 7 L-246, Chariton River Right Bank Tie Back Levee. Levee Realignment.

<u>Grouted Cut-off Wall in a Rockfill Embankment and Construction of a Ring Levee Around the Landside Scour Hole</u>

<u>Cambridge Levee</u>. The Cambridge levee, a non-federally constructed and operated agricultural levee, ties into a railroad embankment as high ground. This railroad embankment that was breached during the 1993 flood is located along the Missouri River's right bank between Slater and Glasgow, Missouri. At the location of the scour hole the railroad embankment consisted of random material with an impervious riverside slope protected with rockfill. The height of the levee corresponds to 10-year flood stage providing protection for farmland and a portion of State Highway 240 between Slater and Glasgow, Missouri, and the well field for Slater, Missouri. During the 1993 flood, about 2,200 linear feet of railroad embankment was breached at river mile 231 along the Cambridge Bend. The flood scoured holes down to bedrock, up to 70 feet deep, washing away the railroad embankment and the adjacent highway that had served as part of the flood protection. The scour hole extended 2,000 feet landward from the railroad embankment toe and the entire foreshore to the river.

The Corps of Engineers together with Gateway Railroad Company unsuccessfully attempted to control the width of the breach by armoring its edges with rock. After the river receded, Gateway Railroad Company and Missouri Department of Transportation reconstructed the embankment using quarry-run rockfill. The reconstruction was on its original alignment, leaving unfilled the deep scour riverward and landward of the breach.

Subsequent flooding in September 1993 and April 1994 allowed water to flow through the embankment and again flooded the highway and the area landside of the embankment. The Corps through PL 84-99 funds attempted to minimize the flow through the rockfill by constructing a grout curtain through the embankment. Grouting was done with a low pressure grout mix consisting of cement, fly ash, and sand with additives to control the migration of the grout below the water table. The grout cut-off wall was extended five feet below the surveyed bottom of the scour hole into the underlying natural alluvial soils that consisted of fine to coarse sand. This soil was grouted with microfine cement to fill the small voids between the sand particles. The volume of grout used was 6,800 cy.

During a May 1996 flood, seepage through the embankment demonstrated that ungrouted "windows" still remained in the cut-off wall. Parametric seepage analyses were conducted with the head and tailwater conditions experienced during the floods before and after the grouting to quantify the amount of seepage reduction that had been accomplished by the grouting and whether additional grouting was justified. This analysis indicated that the grouted wall had significantly reduced the seepage through the embankment by as much as 70 percent and that further reduction was possible with additional grouting. However, no assurance could be made that additional grouting would reduce the seepage to a level acceptable to the local landowners. Consequently, other alternatives were examined that could assure a higher degree of confidence. These included partially backfilling the scour hole with dredged granular material and reconstructing a ten-foot thick impervious blanket on both sides of the railroad embankment. This alternative would have reduced the seepage through the embankment but was extremely expensive.

The most economical solution studied was to construct a ring levee landward of the scour hole that tied into the railroad embankment outside the limits of the breach. As part of the construction in 1997, Highway 240 will also be raised to the height of the ring levee. The plan view of the ring levee is shown in Fig. 8.

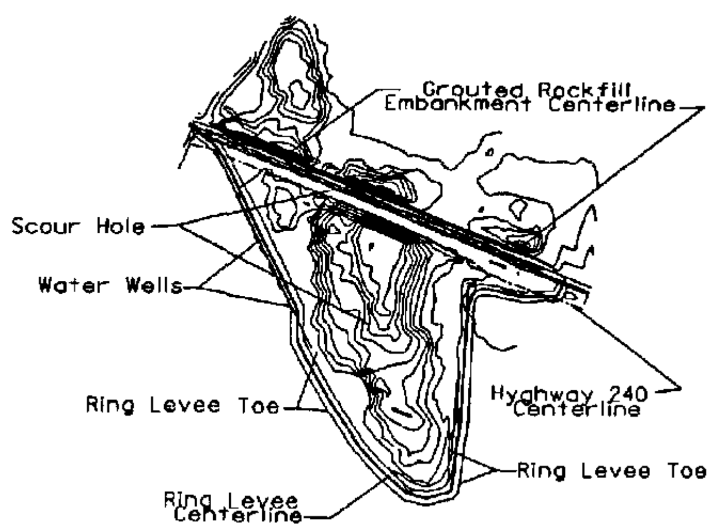

Fig. 8 Cambridge Levee and Glasgow-Saline Railroad. Grouted Rockfill Embankment and Landward Ring Levee.

The average height of the ring levee will be 14 feet, with a ten-foot crown and a 1(V) on 3(H) side slope. The ring levee will be constructed of random fill material consisting of silty sand deposited by the river downstream of the scour hole with a five-foot thick impervious layer on the scour hole side and a three-foot thick impervious layer at the crest. Underseepage calculations determined the setback distance of the ring levee from the scour hole edge to eliminate the necessity of landside underseepage berms. The estimated quantities for the ring levee are 55,000 cy of impervious fill and 86,000 cy of random fill.

HYDRAULIC CONSIDERATIONS

The main stem federal levee units along the Missouri River were originally intended to withstand discharges for stages developed by a 100-year flood event as modified by lakes and reservoirs. (This design discharge was implemented on the system except for the L-246 unit which was modified due to floodway considerations.) The discharges were based on historically measured flows at rated stations along the Missouri River. Selected design flood hydrographs were physically modeled at the Waterways Experimental Station in Vicksburg, Mississippi, to determine confinement effects on the peaks. Backwater studies were then performed to establish the local design water surface profiles for a given reach based on the magnitude of the discharges selected from the physical model, the statistical record at gauging stations, and the reservoir theoretical routing holdouts.

Detailed hydrologic and hydraulic investigations were conducted as the basis for the siting, design, and eventual construction of all the federal levee units. Unlike the federal levees previously discussed, the private levees repaired in 1993 were non-engineered structures where river hydraulics were not considered in their initial geometry or siting.

Various freeboard allowances were developed over time as experience was gained from previous observations. Generally, two feet of freeboard was established, with allowances for dynamic effects, (i.e., momentum velocity vector changes or superelevation, and later, overtopping wedges were added). An overflow slot at the most downstream section was designed to allow certain discharges and filling times based on the volume of the protected unit and the rising limb of the hydrograph. This was a passive, rather than active, filling to reduce damages from scour and sand splays if the levee was overtopped. Tieback levees were also constructed and designed with five-foot of freeboard to prevent domino overtopping and breaching if a unit failed during a flood event.

The design intent for the MRLS stipulated that the foreshore areas would be maintained free of vegetation, sediment and debris deposits. It was assumed that after each flood event, all the deposited materials would be removed and the foreshore area restored to pre-flood elevations. This basic assumption was used as a basic design approach in the development of the water surface profiles. Further, the designs assumed that the navigation and bank stabilization project would be developed along the geometry originally authorized.

Many of the basic assumptions have been invalidated by unforeseen political and environmental initiatives that have restricted maintenance of foreshore areas. The National Environmental Policy Act of 1969 provided additional federal responsibility which impacted the maintenance and restoration of the foreshore area, and the 1970's Missouri River Environmental Assessment allowed the navigation channel to be developed as self-scouring. The overall impact of the changes has been a shift in the stage-discharge relationship — higher flood stages for the same discharge. This stage-discharge relationship has also impinged upon the annual flood event. Flood stage capacity has diminished at Boonville, Missouri, from about 182,000 cfs to around 140,000 cfs, (approximately 25% over the last ten years), while the channel has scoured sufficiently so the bed material is armored against target navigation flows. The annual tonnage of the sediment transport by the river at Hermann, Missouri, has been depleted from approximately 275 to 300 million tons annually to about 70 to 100 million tons per annum. The bed load at this site is less than five million tons per year, which is very near the annual bed load yield.

Levee reconstruction by realigning other than parallel to the flow or by ringing the scour hole, although more economical, can lead to future failures from smaller events. The pocketed water becomes ineffective flow area as the water surface approaches the energy gradient. Also, the resident water generally develops into an eddy. Debris trapped in the eddy may abrade the levee's face yielding additional damage. Also, reconstruction usually adds overbuild for settlement. Although ring levee repairs have followed established practices, theories, and economics, today more factors must be weighed before a repair decision can be made. These factors include Corps of Engineers and FEMA guidelines, environmental restrictions, sponsore requirements, and other political and local economic concerns. The decisions may not always lead to sound river mechanics nor lead to hydraulic longevity of the repair. The 1993 flood repairs followed the established guidelines and criteria. However, after the 1995 flood generated failures of many private levees at or near the same locations as in 1993, speculation was raised about the hydraulic effects of the ringed levee repairs. Field measurements taken after the 1995 flood repairs indicated that the water contained in the ring or pocket had a surface elevation greater than 0.8 feet above the water surface along the opposite bank parallel to the river's flow. The differential was about equal to the velocity head.

Levee repairs completed to both federal levee units and private levees after the 1993 flood performed differently in the 1995 flood event. Generally, the repaired federal levee units performed as designed, whereas several private levees were again compromised. In some cases, failure can be traced to the ring levee repair method that increases water surface profile by reduction of velocity in the "pocketed" area. Experience gained from these two flood events has led to incorporating hydraulic impact into the alternative selection criteria for private levees to minimize future failures.