

Impacts of 1993 Upper Mississippi River Basin Floods on Highway Systems

D. J. HAGERTY, A. C. PAROLA, AND T. E. FENSKE

An investigation of the primary and secondary highway infrastructure in the Upper Mississippi River Basin was conducted to determine the modes and mechanisms of damage caused by the 1993 flooding. Several modes of failure observed are presented. Dramatic examples of scour in sites of highway embankment breaches, scour at bridge abutments on broad floodplains, and scour in rock are presented. Flow over embankments damaged highway embankments and long reaches of highway shoulder and pavement. Slope and embankment failures were caused also by saturation of fill and slope materials and by groundwater effects. Debris transported by floodwater accumulated on secondary roadway bridges substructures, causing catastrophic collapse of structures.

A prolonged wet weather period followed by intense rainfall caused devastating flooding in nine states of the Upper Mississippi River drainage basin during 1993 (1), with consequent extensive damage to primary highway systems. More than \$100 million was requested by state highway departments to repair the federal aid highway system. Less publicized but equally extensive flood damage was caused to the secondary highway system as well. To repair those secondary highways, state, county, and city governments asked for more than \$100 million in addition from the Federal Emergency Management Administration (FEMA).

A field investigation of the damage to primary and secondary highways in Nebraska, Missouri, and Iowa was conducted in September, October, and November 1993. Information was collected and sites were visited in an effort to identify and assess various modes and mechanisms of flood damage.

EMBANKMENT AND SLOPE FAILURES

Long reaches of highways were damaged by scour and erosion, particularly where long approach embankments were situated on broad floodplains adjacent to bridge sites; there was one such situation in Glasgow, Missouri. The Missouri River floodplain at Glasgow is approximately 7.6 km (4.7 mi) wide. A continuous railroad embankment, about 6.9 km (4.3 mi) long, traverses the floodplain from the west to a truss bridge. A similar embankment for Missouri State Highway 240 is located just downstream (south) from the railroad embankment. The main thread of the river flows south in this area but bends just upstream of the embankment to flow east along the embankment to the east side of the floodplain. The river turns to the south, at the east side of the floodplain, where truss bridges carry the railroad and highway across the stream. During the 1993 flooding, the embankments were overtopped and breached, and more than 600 m (2,000 ft) of the embankments were eroded; the failed

embankments are shown in Figure 1. A scour hole more than 15 m (50 ft) deep formed at the location of the breach; sediment from the scour hole was deposited downstream from the breach and on Highway 240 east of the breach.

The failures of these embankments were typical of many similar events that occurred during the 1993 flooding; deep scour holes formed in wide flat floodplains at locations where embankments were breached by overtopping flow. After an embankment was breached, floodplain flow was concentrated through the breach; the concentrated flow typically carried low sediment load to the breach, but large quantities of sediment from the scour hole were deposited short distances downstream from the breach where the flow expanded. The scouring action was similar to clear-water scour at bridge abutments in floodplains. Overtopping damage to roadway embankments was a common occurrence in the affected floodplain areas of the Missouri and Mississippi rivers.

Less severe but more widespread damage was caused to highway embankments in wide, flat floodplains by overtopping flow that did not breach the embankments, as shown in Figure 2. Frequently observed damage included erosion of embankment slopes downstream from overtopped areas as well as erosion of shoulder material and asphalt pavements and undermining of concrete pavements where overtopping occurred.

Although flooding water of the Missouri River and other large streams caused much of the obvious damage to highway embankments and pavements, the intense precipitation also caused severe impacts on drainage structures, with consequent damage to highway embankments and foundations. The capacity of a culvert on a county road in Richardson County, Nebraska, was insufficient to convey flood-period flow, and overtopping flow eroded the overlying roadway and embankment at the culvert, as shown in Figure 3. Figure 4 shows a plunge pool and head cut approximately 5.5 m (18 ft) deep below a corrugated pipe culvert under a section of county road along Rock Creek, near Salem, Nebraska. The slope between the roadway and the creek became saturated generally, as well as downcut transversely (as at the culvert), while the creek simultaneously was eroding the toe of the slope along the outside of a bend. A complex downslope movement occurred in the natural slope, the embankment, and part of the roadway itself, as shown in Figure 5. Layers of alluvium were present in the lower slope near the creek, but the middle and upper slope consisted of a thick bed of loessial (windblown silt) soil. The bed load exposed in the creek included rock fragments as much as 30 cm (12 in.) in dimension. Undercutting of the alluvial soil near the toe of the slope initiated the failure. Large blocks of loessial soil, up to 3 m (10 ft) thick, moved downslope, riding on thoroughly disrupted layers of saturated sand. The large undrained strength of the loessial soils is shown by the steep faces of the sides of the cut around and below the culvert pipe, as shown in Figure 4.



FIGURE 1 Aerial view of embankment breach 6.5 km (4 mi) west of Glasgow, Missouri.

Throughout the flooded region, distress occurred in roadway shoulders, pavements subsided locally, and embankment sideslopes failed because of high groundwater levels. Water ponded in ditches and at raised culvert entrances and seeped laterally through embankments. Seeping water eroded fine-grained soil particles from within embankments and subgrades. Emergent seepage destabilized embankment slopes; localized slumps occurred in destabilized areas, and seepage outflow produced cavities in embankment and slope faces. Figure 6 shows a short stretch of Missouri Highway 59 where the embankment bulged and subsided when zones of soil flowed laterally from the west side of the embankment; the distress was aggravated by downcutting in the ditch along the toe of that embankment. In localized areas on the west slope of the embankment, concentrated outflow had produced cavities in the face of the slope. Large pieces of rock had been dumped into the slump zone in an effort to buttress the slope. The distress in this embankment was typical of the noncollapse, undramatic but widespread damage that occurred in the flooded watersheds far from large streams.



FIGURE 2 Recurrence of erosion damage to section of roadway previously repaired after 1993 flooding [U.S. 65, 9.5 km (6 mi) south of Carrollton, Missouri].



FIGURE 3 Erosion of roadway and embankment caused by overtopping flow (county road, Richardson County, Nebraska).

SCOUR AT BRIDGES

A dramatic impact of the 1993 floods was collapse of highway and railroad bridges caused by scour at piers and abutments. Typical of those failures was the collapse of a railroad span as a result of scour at the west abutment of the previously mentioned crossing over the Missouri River at Glasgow, Missouri. Five trusses, varying from 68 m (224 ft) to 105 m (344 ft) in length, carry Highway 240 between Saline and Howard counties, just downstream from the railroad bridge. Figure 7 shows an aerial view of the collapsed railroad span, the highway bridge, and the scour hole that developed at this location. Four 29.3-m long (96-ft long) approach spans carry the high-

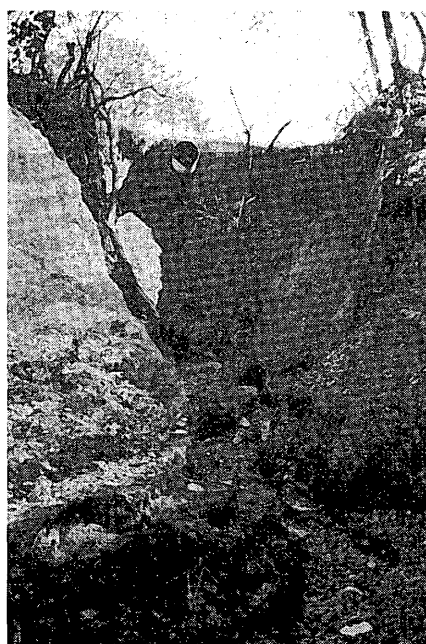


FIGURE 4 Distress and scour at culvert on county road (Richardson County, Nebraska).



FIGURE 5 Slope Failure, roadway damage (Richardson County, Nebraska).

way up to the truss structure. The scour hole was located between the second and fourth piers from the west abutment of the railroad bridge and around the second (E) and third (D) piers of the highway bridge. The approach span of the railroad bridge collapsed on July 29, 1993. All of these highway bridge main trusses are supported on foundations carried down to bedrock; all of the piers for approach spans are supported on four columns each founded on friction piles. The bedrock, at elevations between 168 m (550 ft) at the west end of the trusses and 177 m (580 ft) at the east end, is covered by only 3 to 5 m (10 to 15 ft) of soil under the channel; divers inspected the foundation under the west pier of the easternmost truss on August 19, 1993, and found no sediments over the rock but no undermining of the pier. However, severe undermining had occurred at the scour hole under the foundations of the west approach spans. The floodplain elevation under the approach spans was about 188 m (615 ft) before the flood, the bottoms of the 0.75-m thick (2.5-ft thick) pile cap footings were located at elevation 181 m (593 ft), and the timber piles had been driven 9 to 11 m (30 to 35 ft) below the bottoms of the caps. When divers inspected the foundations of piers D and E on August 12, 1993, they found the deck of the fallen railroad bridge lodged against both north legs of pier D and the northeast leg of pier



FIGURE 6 Embankment failure in Missouri 59 caused by high groundwater levels [8 km (5 mi) north of Craig, Missouri].

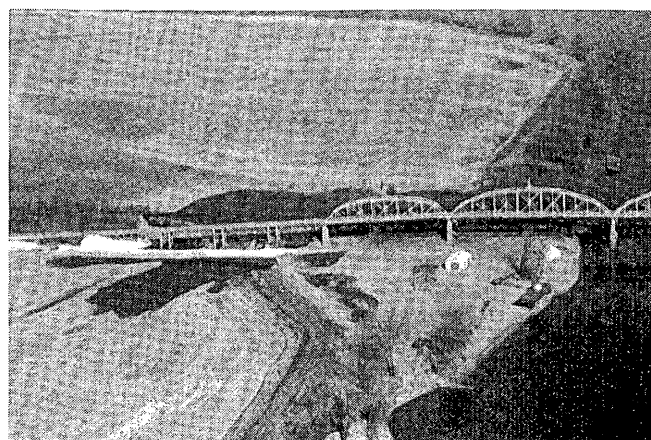


FIGURE 7 Aerial view of scour holes and bridges over Missouri River at Glasgow, Missouri.

E. All of the piles under pier D were exposed, for depths varying between 4.4 and 5.6 m (14.5 and 18.5 ft); in other words, between 11 and 12 m (35 and 40 ft) of floodplain soils had been scoured from around the foundations of pier D. Only about one-half of the pile embedment depth remained. The concrete underside of the north-west pile cap had spalled so that one pile was no longer bearing load; the underside of the northeast pile cap had spalled so badly that all but one entire pile and about 20 percent of another pile had lost contact with the pile cap. At pier E, the floodplain had been scoured down to the bottoms of the pile caps, but only slight undermining of the cap footings was noted. During the flood, pier D oscillated transversely to the bridge axis. To restore support to the friction pile foundation, sheetpiles were driven around the perimeter of the pier, and the space inside the sheetpiles was filled.

The scour hole that undermined the bridges formed 180 m (600 ft) from the right descending bank of the Missouri River. A second scour hole had formed closer to the bank of the stream; the two holes very nearly merged on the upstream side of the collapsed span. Examination of the walls of the scour holes after the floodwaters receded showed that the holes had formed in layered alluvial soils consisting primarily of sands and silts; typically, sandy silt layers 10 to 30 cm (4 to 12 in.) thick were separated by clean sand layers 2 to 5 cm (1 to 2 in.) thick. Thick recent deposits of such soils downstream of the scour hole showed that most of the scoured material was moved only a short distance before the flow velocity decreased sufficiently that the scoured material was deposited. The approach embankments for the bridges form a long barrier to flow over the floodplain to the west of the main bridge site; in contrast, the floodplain to the east of the Missouri River is relatively narrow at Glasgow. The constriction of flow by the approach embankments caused the scour that undermined the bridge piers.

The dominant mechanism of failure was scour by water bearing little load of sediment to the edge of the constriction in flow over the floodplain. The sides of the scour holes contained cavities when the holes were inspected after the floods receded; the cavities appeared to have been caused by groundwater seeping into the holes. The seeping water undoubtedly originated as temporary storage into the floodplain during inundation. The water levels in the holes were still considerably above the level of the Missouri River even in November but were well below the original floodplain elevation. Outflow seepage effects were minor compared with the

scour during the flood, but the outflow seepage caused delayed failures in the scour hole sides; obviously, the exposed surfaces of the scour holes could not be considered necessarily representative of the shapes of the scour holes during the flooding.

Another bridge failure occurred on Iowa Highway 71 approximately 8 mi south of Carroll, Iowa, where a three-span concrete girder bridge failed as a result of scour. Figure 8 shows the collapsed structure and the eroded embankments. Scour of the streambed beneath pier and abutment foundations, the force of floodwaters on the piers, and the weight of the bridge structure caused the pile foundation system to fail. Piles under the abutments failed in combined compression and bending. Overland flow of flood water had contributed to failures in the stream banks downstream from the bridge, and seepage out of the bank faces caused slabbing and toppling failures long after flood recession. The undermining of piers and abutment embankments by scour at this location was an important element in the failure of the bridge.

In some instances, formation of very large scour holes did not produce bridge collapse. A scour hole 550 m (1,800 ft) long and 245 m (800 ft) wide formed near the west end of the steel girder bridge for Interstate Highway 70 over the Missouri River at Rochepoort, Missouri. Two main spans of 168 m (551 ft) each are supported by three piers founded on rock; about 6 m (19 to 20 ft) of scour occurred around the middle pier, with very little scour at the east pier. However, scour uncovered the rock foundations of the first approach pier to the east of the main spans by removing approximately 9 m (30 ft) of floodplain soils. Twelve short spans on the west are supported by an abutment and 12 piers (2 through 13, from the west); the approach span piers are supported on steel H piles driven to rock. The floodplain elevation around the approach spans varies from about 172 to 175 m (563 to 573 ft), with the bottoms of the pile cap footings at about 169 m (555 ft) and the bedrock at about 143 m (470 ft). Soundings on August 18, 1993, showed that the pile cap footings on Piers 3 through 9 had been undermined; the undermining exposed 2.6 m (8.4 ft) of pile at Pier 9 to 5.2 m (17.1 ft) of pile at Pier 7. Corresponding depths of scour were 8.5 m (28 ft) to 11.3 m (37 ft), with the largest scour depth occurring about 300 m (1,000 ft) from the right descending bank of the Missouri River.

Damage caused by scour was widespread in the area of flooding; some of the distress was obvious and dramatic, as in the collapse of major bridges, whereas other distress was much less dramatic but



FIGURE 8 Collapse of Iowa 71 bridge 13 km (8 mi) south of Carroll, Iowa.

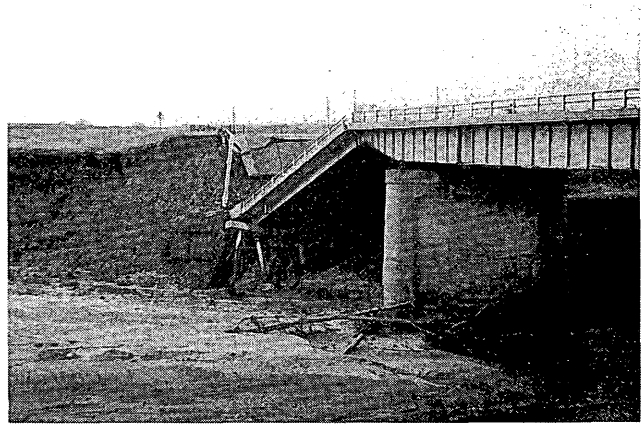


FIGURE 9 Collapse of Nebraska 8 bridge over south fork at Big Nemaha River, near Salem, Nebraska.

still very significant. Typical of the damage to bridges on small streams caused by the 1993 floods was the collapse of one span of a steel girder bridge that carried Nebraska Highway 8 over the south fork of the Big Nemaha River near Salem, Nebraska. The situation at this site was complex because downstream channel modifications have caused general degradation of the stream. The degradation has caused widening of the stream and erosion of the banks. The meandering stream was constricted at the bridge site, so constriction scour during the flood coupled with the general bank erosion to undermine the west abutment of the bridge. Figure 9 shows the affected abutment; collapse of the abutment caused the first span to shift down and to the west and to fall from the adjacent pier. At this location, bedload material as much as 23 cm (9 in.) in dimension was transported out of and along the channel and deposited on a bar just upstream from the bridge site; the bank opposite the bar was being eroded and undercut in autumn, long after flood recession.

In addition to embankment slumps and subsidence, the intense and prolonged rainfall during summer 1993 caused landslides and slope failures that had direct and indirect effects on highways and railroads. In some instances, landslides carried away portions of roadways; in other cases, failing soils blocked roads and streams. Disruption of transportation by the latter processes was not as eye-catching as roadway washouts or as expensive to remedy but still represented a significant impact. In this regard, the deposition of sediments over highways and railroads downstream from scour zones was a serious impact in some communities.

SCOUR IN ROCK

One of the more controversial topics among bridge designers is the prediction of scour depth and extent around bridge piers and abutments founded on rock. The 1993 Midwest floods provided evidence that some rock types and configurations can be eroded. Figure 10 shows the east abutment of a small bridge over Honey Creek near Pawnee City, Nebraska. The banks of the stream consist of loessial soils in the upper banks over mixed alluvial soils in the midheights of the banks, resting on a broken, discontinuous layer of limestone over green-gray fissile shale at the toe of the bank. Scour of the stream bed and the toe of the bank had undermined the bridge abutment. Examination of the bed of the stream showed that the protecting limestone had been plucked off the shale and the more

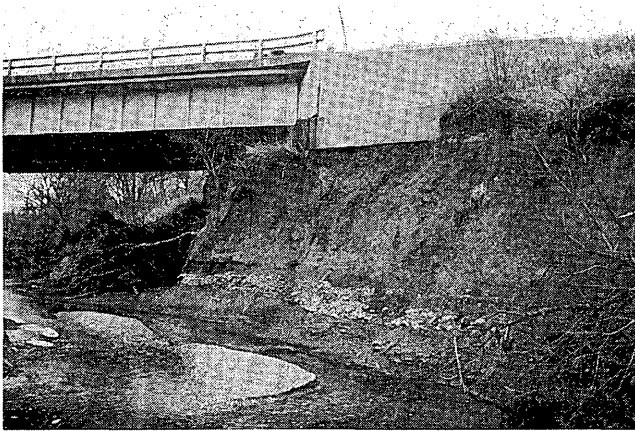


FIGURE 10 Scour effects in limestone and shale strata in bed of Honey Creek near Pawnee City, Nebraska.

vulnerable shale had been eroded as much as 1 m (several feet), as indicated by the elevation of the limestone-shale contact and the unweathered state of the shale exposed in the stream bed. At this site, the resistant limestone had not been worn away gradually; the water had plucked the limestone away in sizeable fragments. A much more dramatic instance of scour of resistant rock occurred at the Saylorville Dam north of Des Moines, Iowa. Figure 11 shows a location a short distance downstream from the crest of the dam, where flow over the emergency spillway cut down through at least 9 m (30 ft) of rock strata. At this site, a siltstone cap rock layer overlies a sequence of gray shales, thin siltstone seams, and thick, black shale layers. Scour along the emergency spillway removed a roadway downstream from the dam, moved very large slabs of siltstone down through the deep trench cut into the shales, and caused a slope failure in a loess bluff on the south side of the stream about 800 m (0.5 mi) downstream from the dam. Figure 12 shows shale boulders up to 0.6 m (2 ft) in dimension that had been moved as bed load far down the scoured trench. The exposed shale boulders had deteriorated through slaking and spalling during the 3 months between flood recession and the date when the photograph was taken.

At a point 14.5 km (9 mi) south of the Saylorville Dam, the Raccoon River scoured the shale beneath a pier foundation of the



FIGURE 11 Scour Canyon in bed of emergency spillway below Saylorville Dam near Johnston, Iowa.



FIGURE 12 Deterioration in shale boulders in bed of emergency spillway below Saylorville Dam.

7th Street Bridge in Des Moines, Iowa. The spread footing supporting the pier located in the main channel was undermined during the flooding and required emergency repairs, as shown in Figure 13, to prevent collapse. The significance of the examples cited in the preceding paragraphs is not that shale was eroded; although some cemented shales are very hard and strong rocks, compaction shales are not cemented and are notoriously vulnerable to scour as well as to weathering. In the examples cited, the vulnerable shale layers were covered and protected to varying degrees by layers of more resistant rock. The extent of the scour in these examples indicates the serious need for additional research on how even very hard and competent rock layers can be affected by water pressures and forces.

DEBRIS

Debris transported by flood flows impacted and accumulated on piers and bridge superstructures, causing adverse effects to both bridge and stream stability. Figure 14 shows the collapsed span of Missouri Highway 113 near Skidmore, Missouri. Debris accumulated on the upstream side of the bridge and blocked flow under the bridge; resultant hydrodynamic pressure forces on the bridge were

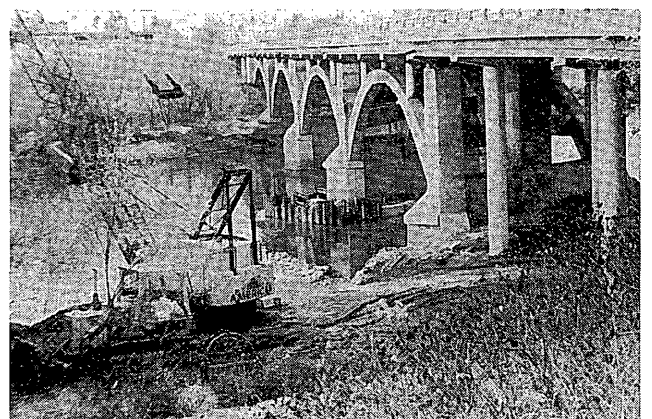


FIGURE 13 Repair of 7th Street bridge in Des Moines, Iowa.



FIGURE 14 Missouri 113 Bridge, near Skidmore, Missouri; collapse caused by debris accumulation.

sufficient to cause simultaneous rotation and translation of individual pile members about the bases of the piers at the stream bed; the pier foundation consisted of timber piles.

A county bridge over the Halfbreed Creek in Richardson County, Nebraska, collapsed because of debris accumulation on a steel pile bent supporting a girder structure. The pile bent consisted of six H piles with the exterior piles battered. The hydrodynamic force developed on the accumulated debris, transferred to the bent, was sufficient to cause the upstream pile to buckle, causing collapse of the superstructure.

At other sites, debris accumulations on piers caused scour holes to form under and upstream of the accumulations and deposition to occur downstream of the accumulations. At some sites, flows were deflected by the accumulated debris, causing scour at the faces of abutment embankments, erosion of streambanks, and widening of channels.

SUMMARY

The 1993 floods caused dramatic damage to transportation facilities in the Midwest. Scour at bridge sites caused pier and abutment fail-

ures with consequent collapses of support spans. Forces associated with debris accumulations on bridge superstructures and substructures were factors in the collapse of at least two bridges. Bridge failures occurred not only on the Missouri River but also on many smaller streams. At a few sites, scour occurred in "resistant" rock.

Constriction of flood plain flow also caused widespread damage, including failures, in approach embankments at bridge sites. Flood flow over embankments caused extensive damage to roadway pavements, shoulders, and downstream slopes of embankments. Less obvious but more common distress was caused by inadequacies in drainage facilities, with consequent destabilizing effects on embankments.

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REFERENCES

1. Parrett, C., N. B. Melcher, and R. W. James, Jr. *Flood Discharge in the Upper Mississippi River Basin*, 1993. U.S. Geologic Survey Circular 1120-A, 1994.

The opinions and conclusions expressed herein are those of the research agency personnel; they are not necessarily those of TRB, the National Research Council, or the U.S. Government.