OBSERVATIONS ON THE CAUSES OF BRIDGE DAMAGE IN PENNSYLVANIA AND NEW YORK DUE TO HURRICANE AGNES

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This paper evaluates the performance of bridges subjected to a major flood, determines the adequacy of design standards based on bridge performance, and recommends revisions to design standards where inadequacies are apparent. Hurricane Agnes caused severe flooding in Pennsylvania and New York, and several bridges and highways that were damaged by the floods in those states are discussed. The two major causes of bridge damage were scour at abutments and piers and impacting debris.

•HURRICANE AGNES spawned the floods of June 1972, which have been called the greatest natural disaster in the history of the United States. Its impact on certain areas of the Northeast may require several years to eradicate. Although many of the bridges in Pennsylvania and New York were damaged extensively or destroyed, most survived and soon were reopened to traffic after undergoing necessary repairs and maintenance.

A few structures were less fortunate, particularly those struck by large amounts of current-driven debris and others that were subjected to extensive scour behind and beneath their abutments and at their piers. The bridge damage, however, seems remarkably slight in relation to the total number of bridges involved and the unprecedented flows. In those situations involving large streams in northeastern Pennsylvania and the southern tier area of New York, flows exceeded the largest previously experienced floods by a wide margin. For example, the June 1972 flood discharge of the Susquehanna River at Wilkes Barre, Pennsylvania, was approximately 1.5 times the magnitude of previous historic floods, which occurred in March 1865 and March 1936. Although the flood frequency of the Susquehanna's peak discharge during this record-breaking flood has not been definitely established, all of the experts seem to agree that the recurrence interval is substantially greater than 100 years. In New York, the recurrence intervals of the flooding also are much greater than 100 years at many sites.

Although the June 1972 flood was a maximum of record, many bridges survived the flood with little if any damage. These bridges were of particular interest because they obviously have features that enabled the structures to survive a severe test. The outstanding performance of these structures is a positive indication of features that constitute desirable design standards. The case history approach is used to discuss a few of the most revealing situations that were encountered as they relate to the causes of bridge damage.

DEBRIS

The most obvious cause of damage was waterborne debris that struck the bridges and collected on the superstructures and piers, as shown in Figure 1. Even in the absence of structural damage, debris removal alone was costly. At one location involving a major structure more than 1,400 ft long on the Susquehanna River in Pennsylvania, personnel of the Pennsylvania Department of Transportation and the Federal Highway Administration estimated that the cost of debris removal from the bridge deck, piers, and superstructure would approach $80,000.

Inspection of several steel bridge spans that had been carried away by the floodwaters indicated that the force of the impacting debris, in addition to, or in combination with, the pressure of the flowing water on the lodged debris, was largely responsible for this type of damage. In several instances, large portions of the piers were ripped away when the spans were dislodged from their supports. Stone piers or combination stone and concrete piers supporting multispan structures seemed to be particularly vulnerable. Considerable cracking of the pier caps also was noted, as the example shown in Figure 2 indicates.

Simply supported spans seemed to be most vulnerable to the dynamic forces produced by floodwaters and impacting debris. Bearing devices at the piers apparently did not resist the lateral forces that developed. In contrast, multispan stone and concrete arch bridges (Fig. 3) seemed to withstand these forces best, probably because of the continuity at the piers afforded by this type of construction.

In some cases it appeared that debris completely blocked the bridge openings and caused the already swollen river to increase further and inundate upstream areas. As the floodwaters progressively increased in depth, they eventually were able to overtop the bridge or its approaches. This resulted in many highway washouts and large amounts of damage to highway pavement that might not have occurred if the full capacity of the bridge opening and the river channels had been used. Adequate provision for highway-embankment overflow prevented the destruction of many bridges.

In several instances, overflow sections provided an effective means of reducing the high potential for debris damage at structures where heavy deposits of drift accumulated, clogged the bridge opening, and prevented the full hydraulic capacity of the waterway area from being used effectively. The relief provided by overflow reduced the pressure of the flowing water on the debris lodged in the bridge openings, which resulted in less structural damage than would have occurred otherwise. Some of the drift was conveyed over the roadway at the overflow sections, bypassing the bridges entirely, without being forced to enter the bridge openings. It was apparent that a judicious provision for overflow can appreciably reduce the structural damage caused by the impact of debris.

Reinforced concrete piers at the newer bridges developed a greater resistance to cracking than the unreinforced concrete, stone, or combination stone and concrete piers of the older bridges. The only exception, in this regard, was the old multispan stone arch bridges, which proved to be extremely damage-resistant. The superiority of reinforced concrete over unreinforced concrete as a construction material for piers was clearly evident.

One victim of debris was the James Street bridge at North Towanda, Pennsylvania. It was reported that the steel bracing of the trusses that supported the roadway deck was struck by at least one house trailer, possibly several buildings, a large amount of debris, and a variety of flood trash that collected on the vertical members and chords. Figure 4a shows conditions near the east abutment during the height of the flood. Note the large deflections of the vertical members of the upstream truss under the combined forces exerted by the flowing water and debris. Figure 4b shows the deflection of some of the members of the downstream truss under similar conditions. Both photographs were taken just before failure. A close examination of Figure 4b seems to indicate that at least two vertical members had been sheared from the lower chord of the truss under the action of the dynamic forces. Also note the deflection of the guardrail on the deck, which further indicates the forces on the bridge.

SCOUR

Scour at bridge abutments and piers was the second most obvious cause of damage. In many cases, the scour that occurred around bridge piers was amplified by the debris that collected on the piers. The debris increased the turbulence of the floodwater, which further increased the tendency to scour.

North Street Bridge at Wilkes Barre, Pennsylvania

With the exception of its end spans, the North Street bridge at Wilkes Barre, Pennsylvania, was totally destroyed. The piers tipped because of scour and, in some cases,

Figure 1. Debris deposited on bridge by floodwaters.

Figure 2. Cracked pier cap on Towanda Creek bridge in Powell, Penn.

Figure 3. Arch bridges, such as the Market Street bridge in Wilkes Barre, Penn., were most damage-resistant.

Figure 4. Large deflection of (a) the upstream truss and (b) the downstream truss of the James Street bridge in North Towanda, Penn.

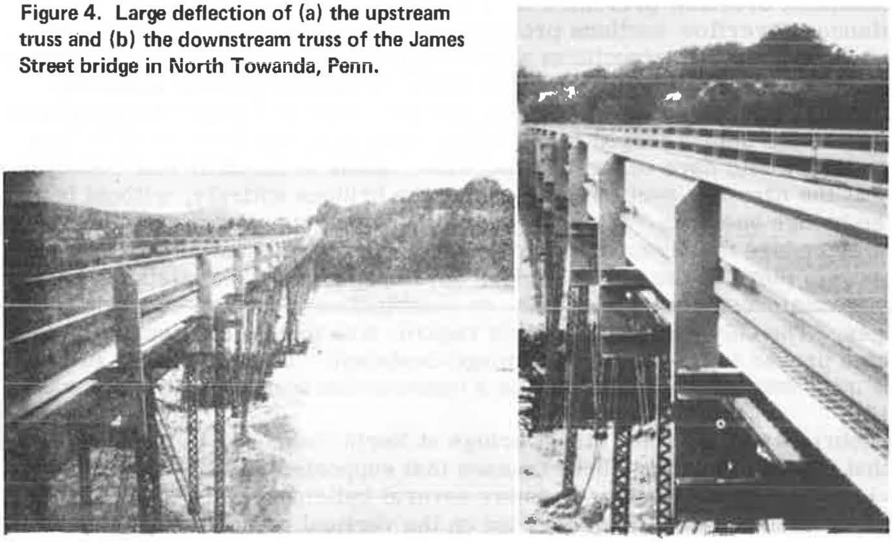

Figure 5. Post-flood remnants of the James Street bridge.

Figure 6. Exposed piling and undermined abutment of Chemung River bridge.

completely fell over. This bridge was constructed many years ago, and the details of its substructure design are unknown. It was reported that some of the piers, but not all, had been supported by timber piling. The City of Wilkes Barre is underlain by numerous coal mines that reportedly have undergone subsidence in recent years. Mines are known to be located under the river at the bridge site.

James Street Bridge at North Towanda, Pennsylvania

The James Street bridge at North Towanda, Pennsylvania, which fell victim to debris also, was adversely affected by scour. After the Susquehanna's flow had subsided sufficiently, the Pennsylvania Department of Transportation wisely arranged for an underwater inspection of this structure. The following remarks are excerpted from the diver's report:

> Pier No. 7 can best be described as being supported by its own inertia. With the exception of a small area of not over 20 sq ft at the downstream left corner [downstream is toward the left in Figure 5], there is no ground support for the pier. The undercut at the upstream end is 40 in. high. The pilings, which in 1969 were measured at 10 to 12 in. in diameter, are now eroded to 3 in. in diameter. At least 2 piles under the upstream nose of the pier have been eroded completely in two. I was able to pass completely under the pier at a point directly below the upstream bridge truss. In this area the thickest pile measured was 5 in. in diameter. Toward the downstream end a pile 8 in. in diameter was found. I was unable to measure the piles on the interior rows downstream of the point I passed under the pier, but they felt as if the radius was larger, and the piles were definitely less spongy. The sand and gravel carried in the bed load of the river is effectively eroding away the wood in the piles.

Bridges on the Chemung River, New York

Many bridges in New York State survived the flood principally because their abutments were founded on piles. Three excellent examples of abutment scour were observed at bridges on the Chemung River. At the bridge near Lowman, although the abutment footing and a considerable length of piling beneath the footing were exposed (Fig. 6), the piling retained its load-carrying capability, and the structure remained in place in spite of the large amount of scour that occurred. With the exception of one of the abutments of the bridge near Lowman, which will be discussed subsequently in more detail, none of these structures was protected by spur dikes at the time of the flood. A careful examination of the concrete abutments failed to reveal any indication of cracking damage or other evidence of structural distress due to differential settlement or abutment rotation. After the abutments were underpinned and the washed-out sections of the approach embankments were reconstructed, the bridges were reopened.

Tioga River Bridge at Presho, New York

Another interesting situation involved a breaching of the approach embankment behind one of the abutments at a county bridge on the Tioga River at Presho. Although the footing and approximately 7 ft of piling were exposed (Fig. 7), the underlying pile foundation retained its supportive capacity and the abutment remained intact.

A short distance landward from the breach along the approach embankment, a section of the highway in a sag vertical curve was overtopped, several hundred feet of pavement were displaced, and the downward slope of the embankment was severely eroded. Water, cascading over the embankment, fell several feet to the toe of the fill and eroded the unprotected downstream slope. Although the pavement shown in Figure 8 was completely destroyed, the underlying embankment sustained surprisingly little damage. Field reconnaissance indicated that the floodplain upstream from the damaged highway carried a large quantity of overbank flow. A section of railroad track owned by Penn Central crosses the floodplain parallel to the river channel and intersects the highway within the sag. The trackage also sustained considerable damage (Fig. 8). Extensive repairs and maintenance were required before either rail or highway service could be restored.

Canisteo River Bridge at Erwins Junction, New York

Another noteworthy example of the effects of scour was provided at a site on the Canisteo River at Erwins Junction. Figure 9 shows the location of the dual bridges (indicated by the circle) and the alignment of US-15. The Canisteo River channel is located at the extreme south side of a wide valley, at the toe of steeply sloping hills. When sufficiently high flood stages are experienced, the bridge opening becomes fully eccentric in relation to the area occupied by the river and a large quantity of flow is carried by the floodplain, which is located entirely on the north bank. As shown in Figure 9, the Tioga and Canisteo Rivers meet to form the Chemung River, a few thousand feet downstream. When the Tioga discharges a large flow at this confluence, it is capable of creating backwater at the Canisteo River bridge.

At this location, US-17 borders the north side of the floodplain, paralleling the Canisteo River. US-17 is spanned by a grade separation structure about 1,700 ft north of the Canisteo River bridge at the Erwins Junction interchange. Extensive hydrologic and hydraulic design studies were made at the time this project was designed. These studies were used to design the Canisteo River bridge, which survived the flood with only minor damage to the north abutment of the upstream structure. During the June 1972 flood, the approach embankment at the north abutment was slightly scoured, and some material was eroded beneath the abutment footing, exposing about 2 ft of piling (Fig. 10). In view of the fully eccentric condition that developed and the large quantity of overbank flow that reentered the main channel at the bridge opening, it was surprising and perhaps fortuitous that the north abutment did not sustain far greater damage than the nominal amount described. The transverse movement of a large overbank flow along a highway embankment toward a bridge opening causes substantial embankment scour in the vicinity of the abutment.

Some relief for the Canisteo River bridge was provided by the grade separation structure at the interchange of US-15 and US-17 at Erwins Junction. The overflow at this interchange apparently helped to prevent more serious damage at the north abutment of the Canisteo River bridge. Perhaps the most significant factor in limiting the scour damage at the abutment and in the bridge opening was the presence of a row of large trees at the edge of the floodplain, parallel to the main channel. This line of trees extends upstream from the abutment, along the top of the riverbank, for a considerable distance. This natural feature apparently was extremely effective in preventing excessive scour damage at the abutment and in the vicinity of the bridge opening.

In contrast to the minimal damage sustained by the bridge opening, the channel downstream was extensively scoured. The north bank of the channel was lined with a dense growth of heavy trees, whereas the south bank was treeless. Both banks were subjected to large quantities of overflow. The treeless bank was severely scoured and required considerable maintenance. In comparison, the bank with trees sustained only slight scour damage because of the stabilizing influence of the heavy overgrowth.

Although the Canisteo River bridge was not overtopped, it was evident from the high-water marks on the upstream and downstream sides of the approach embankment at the bridge that its entire waterway must have been utilized. This structure survived the flooding with little damage and was never closed for repairs.

The situation at the interchange of US-15 and US-17, just north of the Canisteo River bridge, was somewhat less satisfactory. Its abutments were constructed on spread footings. Piles were not used because it was considered extremely unlikely that the river would ever flow through this interchange, and, in addition, an adequate bearing capacity for abutment support was available. It appeared that the high stages in the Canisteo were increased by backwater caused by the Tioga, and, as a consequence, US-17 at Erwins Junction interchange was inundated and the interchange structures were forced to convey a substantial flow. This flow caused a large amount of scour at the interchange abutments and resulted in substantial damage as shown in Figures 11 and 12. Both abutments were extensively undermined with the scour approximating 3 ft at some points beneath the footing and extending laterally 10 ft or more from the breast wall of the left abutment. The maximum depth of scour at the abutment shown in Figure 12 was 4½ to 5 ft. The state department of transportation felt that the structure

Figure 7. Approximately 7 ft of exposed piling beneath abutment of Tioga River bridge.

Figure 8. Approach damaged by overflow on Tioga River bridge.

Figure 9. Location and alignment of highways at bridge site. Canisteo River bridge is indicated by circle.

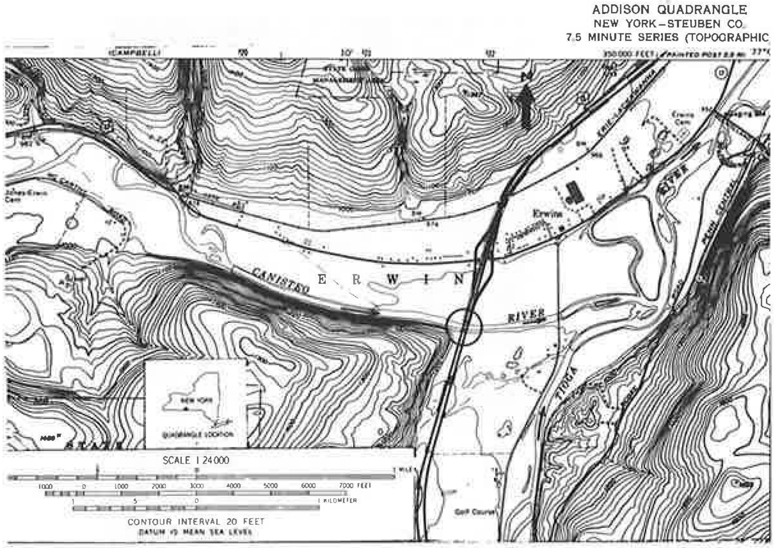

Figure 10. Upstream view of scoured bridge abutment and approximately 2 ft of exposed piling on Canisteo River bridge.

Figure 11. Timber cribbing supporting US-17 interchange bridge until abutments could be underpinned.

Figure 12. Scour beneath and behind abutments on US-15 interchange bridge.

Figure 13. Settlement due to scour on Chemung River bridge in Elmira, N.Y.

Figure 14. Rockfill spur dike near Susquehanna River bridge in Nanticoke, Penn., during 1964 flood.

Figure 15. Post-flood condition of floodplain between abutment and adjacent pier of Susquehanna bridge.

Figure 16. Remnants of earthfill spur dike near Chemung River bridge near Lowman, N.Y.

Figure 17. Enlarged scour hole upstream from Chemung River bridge in Waverly, N.Y.

survived because the steel superstructure prevented collapse. The structure was closed to traffic and braced by timber cribbing until the footings could be underpinned.

The situation provided a striking example of the importance of hydraulic and hydrologic considerations in highway design. Here were two modern bridges on the same highway separated by only a few hundred feet of roadway embankment. Both structures were designed to the same high structural and geometric standards. The major difference was that the Canisteo River bridge was designed to convey "hydraulic traffic" as well as vehicular traffic. It performed well and suffered only minor damage. In contrast the Erwins Junction interchange bridge was not designed to convey river flow; its function was to carry vehicular traffic only.

Chemung River Bridge at Elmira, New York

In those cases where the abutments were set back from the edge of the main channel, it was noted that a pier often was located near or at the top of the bank where the main channel and floodplain merge. Unfortunately a pier in this location appeared to be the most vulnerable of all to scour. Figure 13 shows a pier located near the edge of a river channel. The structure spans the Chemung River at Elmira, New York. As shown in the figure, the pier plunged into the riverbed as a result of scour and subsequent settlement. The pier apparently collected a large amount of debris, which may have increased the amount of scour. It is significant that the structure is continuous at the pier. In the author's opinion this feature was largely responsible for supporting the bridge until it could be adequately braced, thereby preventing collapse or serious damage to the superstructure due to the loss of support and settlement of the pier. The benefits of continuity in bridge structures were clearly demonstrated here.

Susquehanna River Bridge at Nanticoke, Pennsylvania

In the early 1960s, a 300-ft rockfill spur dike was constructed at an abutment of a bridge on the Susquehanna River at Nanticoke, Pennsylvania, after scour undermined an abutment and adjacent piers. Figure 14 shows the spur dike during the March 1964 flood and the turbulent conditions that existed near the dike's upstream tip where the overbank flow reentered the main channel. A comparison of the scour after two floods, both before and after the dike's construction but prior to the June 1972 flood, indicated that the dike had been effective in arresting the scour. During the flood of June 1972, the dike was overtopped by about 3 ft of water, and its effectiveness in controlling scour under such adverse conditions was severely tested. The dike remained intact and was remarkably effective during the June 1972 flood.

When the dike was examined after the flood, there was little evidence of scour other than a small, slightly eroded area near the upstream tip of the dike where a minor amount of vegetation was removed by the floodwater. There was no apparent damage along the streamward face of the dike. Figure 15 shows the area directly under the bridge near the abutment. Note the small trees growing in the area between the pier and the abutment. Because these trees were not uprooted by the floodwaters it is concluded that little if any scour occurred in this area. Prior to the spur dike's installation, the amount of scour was so extensive here that the abutment and adjacent piers were in grave danger due to undermining.

Another significant factor in the dike's excellent performance, in view of the overtopping that occurred, was the size and weight of the rock that had been used in its construction. The rock appeared to be sufficiently massive, which permitted the fill to resist the destructive effects of overtopping and to withstand the potentially damaging currents that flowed around the dike, especially near its upstream tip.

The trees and heavy brush that have grown up around the spur dike also helped in preventing the development of erosive velocities in the overbank area adjacent to the spur dike. This example illustrates that clearing and grubbing operations should be limited to that part of the right-of-way actually necessary for the construction, especially at river crossings. Full advantage should be taken of the available flow retardance of the existing vegetation. If possible, the trees and ground cover in the vicinity of the tip of a proposed spur dike should not be cleared.

Chemung River Bridge Near Lowman, New York

At a site on the Chemung River near Lowman, New York, a spur dike was constructed at an abutment to provide scour protection. A small branching channel of the Chemung rejoins the main channel near the upstream tip of the dike. The floodplain upstream from the bridge carried a large quantity of flow during the June 1972 flood. Although this earthfill spur dike was overtopped and largely washed away as shown in Figure 16, the upstream side of the approach embankment remained intact and survived the flood with no apparent damage to itself or to the vegetation growing on its slopes. Only minor amounts of erosion occurred at this abutment. In contrast, the abutment on the opposite riverbank did not have the benefit of spur-dike protection and was extensively scoured. Of the four Chemung River bridges discussed in this report, the bridge near Lowman was the only one with a spur dike at the time of the flood. (Since that time, New York has constructed spur dikes at the abutments of three of the four Chemung River bridges referred to.) The damaged spur dike was replaced at a fraction of the cost of a new structure, and reconstruction was accomplished with a minimum of traffic interruption. A new spur dike also was installed at the abutment that had been severely scoured (5).

Chemung River Bridge at Waverly, New York

At another location on the Chemung River at Waverly, New York, the floodplain on the west bank upstream from the bridge is several thousand feet wide and was inundated to a depth in excess of 6 ft. A spur dike would have provided an extra measure of safety against the possibility of scour damage, but its absence did not result in damage to the west abutment in this instance. According to the New York DOT, there was less debris at this site than at the other Chemung sites, and the west abutment was afforded some protection by its location, which is on the inside of a gentle bend in the river. Note the extensive scour hole, shown in Figure 17, at the riverbank where the floodplain and river channel join, upstream from the abutment. The embankment was intact and undamaged in the vicinity of the abutment. Because of the topography of the floodplain, a large portion of the overbank flow apparently reentered the main channel at a depression some distance upstream. A scour hole of much smaller dimensions had existed at this depression for several years. The June 1972 flood simply enlarged the existing scour hole. The most extensive damage to the bridge occurred at the abutment on the opposite bank where more than 5 ft of scour occurred beneath the footing and exposed the piling. Because the floodplain is practically nonexistent on the east side of the river, a spur dike would not have helped here.

It should not be inferred from this example that a preformed scour hole upstream from a bridge abutment is suggested as a means of protecting the abutment from scour due to overbank flow or that it is recommended in lieu of a spur dike. Floodplain topography played a major role in determining that a large portion of overbank flow would enter the main channel well upstream from the structure. In fact, the location of the scour hole may have been determined by the topography of the floodplain. But, as mentioned previously, extreme floods tend to generate complex conditions that are all but impossible to anticipate. Unfortified natural features, by themselves, cannot be relied on to always provide sufficient protection when rare and unusual conditions are experienced.

Chemung River Bridge at Chemung, New York

The quantity of scour at this site was unusual inasmuch as there was much scour and no structural damage at the west abutment and its adjacent piers. A large quantity of material was deposited in this area. The deposit extended downstream from the bridge for a considerable distance.

The east abutment was extensively scoured: Approximately 7 or 8 ft of scour occurred beneath the abutment footing. Also the highway approach embankment was breached behind the abutment. The highway bridge abutment had been connected by a levee to the abutment of a nearby upstream railroad bridge to provide scour protection. During the flood, this levee was overtopped and severely eroded, thereby enabling the floodwaters to scour the highway bridge abutment. The levee was rebuilt to a substantially higher elevation and riprapped to provide protection against a reoccurrence. At the highway bridge abutment, concrete slabs were placed in conjunction with stone riprap to provide stouter protection than could be afforded by stone riprap alone.

Lehigh Valley Railroad Bridge at Athens, Pennsylvania

Further downstream on the Chemung at the Lehigh Valley Railroad bridge in Athens, Pennsylvania, another excellent example of abutment scour occurred. It provides further corroboration of a previous statement that scour at bridge abutments largely depends on the degree of flow constriction imposed by the bridge opening. The location of the bridge and the embankment alignment are indicated by circle No. 1 in Figure 18. The east abutment of this bridge is located at the edge of the riverbank. The railway embankment traverses the floodplain diagonally, which causes a large amount of overbank flow to funnel into the bridge opening at the east abutment. Turbulence in the eddy zone, which resulted from the mixing of the overbank flow with the flow in the main channel, caused a large scour hole to form upstream. Resulting scour damage is shown in Figure 19. A spur dike would have helped to prevent scour at this abutment.

This bridge had a number of aspects that are worthy of comment. It consists of five simply supported through trusses on stone piers and abutments. The structure was obviously built many years ago. To ensure that the structure would stay in place and survive the effects of the flood in a structurally sound and usable condition required that a fully loaded freight train be driven onto the bridge to provide extra weight, or ballast, and parked on the deck until the rampaging waters of the Chemung receded. This probably saved the bridge. Nevertheless, the first pier streamward from the west abutment experienced substantial settlement during the flood and was reported to have settled 5 ft, sinking virtually straight down. Near the height of the flood, a standing wave, heavy turbulence, and a strong concentration of flow were observed in the vicinity of the pier that experienced the 5-ft settlement. This adverse flow condition may have been due in part to the large quantity of overbank flow that entered the river at the left abutment, which caused the flow in the channel to deflect toward this pier and concentrate in its vicinity.

After the flood, steel cribbing was placed around the pier for support. It was reported that an attempt was made to underpin this pier, but foundation conditions made it impossible to drive piles. The bridge is still in use although its track profile (Fig. 20) is deflected vertically in the vicinity of the sunken pier. The west abutment did not appear to have been damaged.

Another interesting aspect of the Lehigh Railroad bridge problem is concerned with the historic flood profile at the site. Figure 21 shows the water-surface profiles for several historic floods of the Chemung River in the reach where the bridge is located. The sharp break in the slope of the water-surface profile at the bridge for the 1946 flood indicates that this structure was at least a partial high-water control during the 1946 flood for a substantial reach of the river upstream from the bridge. The sharp break in slope is indicative of a large increase in flood flow velocity at the bridge. A similar condition possibly existed at the site during the recent flood and would, in that event, have been a significant factor in the amount of scour that occurred.

The location of Tozier's Bridge, indicated by circle No. 2 in Figure 18, is also shown in Figure 21. Figure 21 shows that this structure was extensively inundated by the 1946 flood; however, it was totally destroyed by the June 1972 flood. Debris, scour, and the extensive inundation combined to cause the failure in this case. The flood profiles were used in designing the bridge openings of the Chemung River bridges at Waverly and near Chemung. Their respective locations are indicated in Figure 21 by the designations D.L.& W. R.R. Bridge and proposed bridge site. The damage due to the June 1972 flood might have been much greater at both of these structures if the information provided by the 1936 and 1946 flood profiles had not been taken into account when the bridge openings were designed. It is noteworthy that the county highway bridge located immediately upstream from the structure designated on the flood profile as the D.L.& W. R.R. Bridge, the Waverly bridge, was totally destroyed by the June 1972

Figure 18. Athens, Penn.: Circle No. 1 shows Lehigh Valley Railroad bridge and approaching track alignment; circle No. 2 shows location of Tozier's Bridge.

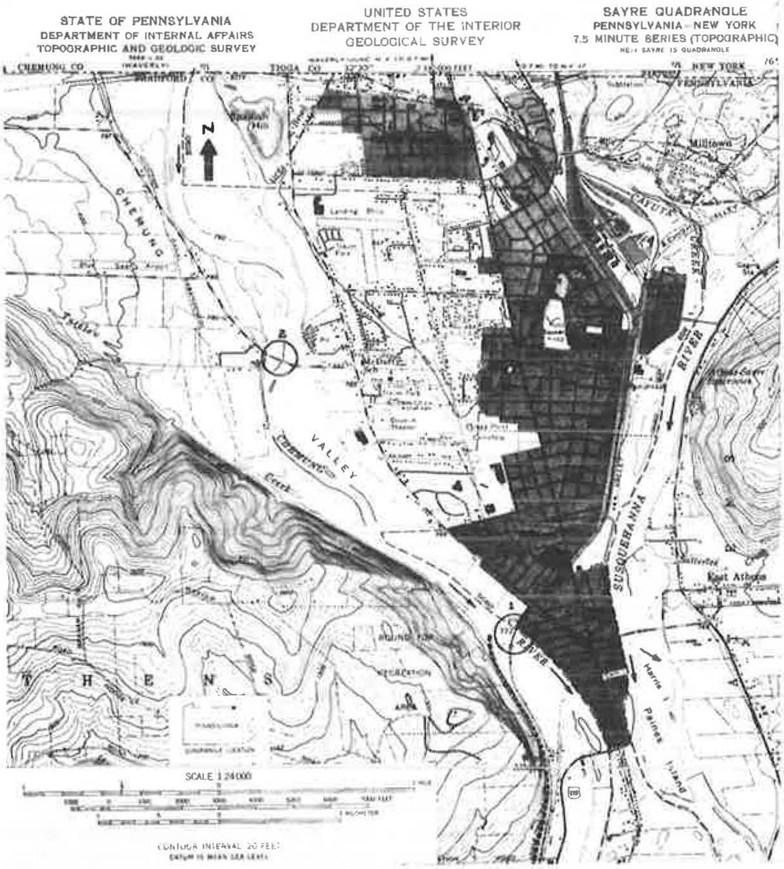

Figure 19. Upstream scour hole, eroded approach embankment, and damaged abutment of Lehigh Valley Railroad bridge.

Figure 20. Downstream view of Lehigh Valley Railroad bridge showing pier settlement.

flood. Historic flood profiles are very useful in the design of replacement and new structures.

County Highway Paralleling the Tioga River at Presho, New York

Highways that parallel streams along the top of a riverbank are vulnerable to undermining. One segment of roadway that parallels the Tioga River along the top of the riverbank at Presho, New York, was badly damaged by overflow during the June 1972 flood. The streamward side of the highway, shown in Figure 22, was extensively undermined, but the damage would almost certainly have been far greater if the embankment slope had not been heavily riprapped. The pavement consisted of 8-in. reinforced concrete with a 5-in. asphalt overlay. In one segment, the asphalt overlay was badly scoured and exposed the concrete, which in turn was extensively undermined. The damage to the pavement appeared to have been caused by trees and other debris that were carried by the stream as well as by the erosive action of the floodwaters. In situations such as these, it probably would be neither possible nor desirable to completely eliminate all damage, but a well-protected riverbank bordering the edge of the roadway in the overtopped area can help to substantially reduce inundation damages.

Susquehanna River Bridge at Dewart, Pennsylvania

Many of the Susquehanna River bridges in Pennsylvania had obviously been designed with overflow in mind. In checking bridge abutments for scour damage, many situations were encountered where overflow had occurred at some point along the approach roadway embankment. In each instance no damage was sustained by the bridge abutments. The embankment approaches seemed to have been intentionally constructed with a slight dip in their longitudinal profiles to permit overtopping when the anticipated floodwaters exceeded some predetermined elevation.

Evidently the concept of using highway embankment overflow as a means of effectively conveying flood flow was understood and successfully employed by the bridge builders of yesteryear. The wisdom of this thinking and the effectiveness of this method in preventing scour damage at bridge abutments were proved many times during this flood.

The overflow concept apparently was used in the design of the Susquehanna River crossing at Dewart, Pennsylvania. At this site the highway embankment traverses the east bank floodplain on a low profile, which gradually rises to the bridge. The downstream edge of the embankment had been paved with a concrete apron that was effective in preventing scour damage, even though the roadway had been overtopped by 7 or 8 ft of fast-flowing floodwater. An additional factor was the difference in elevation, several feet in some sections, between the crest of the pavement at the shoulder's edge and the downstream toe of the embankment. The overflow section was several hundred feet long and obviously provided considerable relief for the bridge during the flood. It appeared that the total absence of damage to the structure and its abutments was directly related to the availability of an adequate overflow section, which conveyed drift as well as floodwater. Although it was clear that drift had struck the bridge, there was no evidence of damage or structural distress. It also was apparent that the downstream slopes of highway embankments that are designed for overflow, or that are subject to overtopping, may require protection from debris and scour by paving, riprap, or some comparable type of ballasting if the expected debris is heavy and the anticipated drop between the upstream and downstream water-surface elevations is large.

The pattern of reduced damage, due to drift and scour, where overflow occurred was repeated so often at the bridge sites in Pennsylvania and New York that some consideration should be given to incorporating an overflow provision in the design criteria.

OTHER CAUSES

Bridges that were located in the proximity of bends in river channels also sustained damage. In some cases, several spans of multispan, simply supported bridges were washed away because of flow concentration in the channel near the outside of the bend. The nonuniform flow distribution contributed to the failure of the Susquehanna River bridge at Lacyville, Pennsylvania. The bend is located upstream from the structure. In traversing the bend, the flow tended to concentrate on the east side (outside) of the channel, and, as a result, the east abutment was badly scoured. The bend also contributed to a severe debris problem at this site. The two spans that were destroyed probably were lost because of the combined effects of the bend, scour, and debris.

When the performance of the bridges that had been subjected to the severe conditions was compared, it was evident that those that had been designed and built in accordance with high structural and geometric design standards generally survived the flood in better condition than those that had been designed to a lower standard. However, the June 1972 floods clearly demonstrated that designing to these high standards alone is not sufficient if essential hydrologic and hydraulic considerations are overlooked or if inadequate provisions are made to accommodate those considerations.

One bridge designed to low standards is the bridge on Schrader Branch of Towanda Creek at Powell, Pennsylvania. At this site, a concrete pier was found to be completely cracked from top to bottom over its entire cross section in the direction of its width (Fig. 23). In addition the spread footing was completely broken away from the pier shaft (Fig. 24), which gave it a wedge-shaped appearance. Investigation revealed that the pier footing apparently had been poured on the riverbed, which is composed of loose, granular material. It appeared that the weight of the bridge was primarily responsible for preventing the pier from toppling over. There was no evidence of a pile foundation beneath the footing. Lacking the support of an adequate foundation and the strength provided by steel reinforcement, the pier subsequently cracked under the applied forces and loads. Although it was impossible to determine the extent of the pier damage attributable solely to the June flood, it is likely that the pier was in a weakened condition before the flood occurred. It was evident that a previous attempt had been made to seal and grout the crack. This pier was struck by a large amount of debris, which apparently was traveling at a high velocity at impact.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

It was concluded from the examples cited that a pile foundation of sufficient length or footings founded at a sufficient depth are needed to avoid abutment or pier failure in erodible soils. Specifications in design standards giving arbitrary depths of piles for protection against scour should be avoided. Pile length or depth of spread footings should be based on the anticipated depth of scour as well as bearing capacity. In this regard, a designer should not become overly concerned that stub abutments are unduly scour-prone. A stub abutment is as acceptable as a full-height abutment if the depth of the foundation is sufficient to provide adequate structural support where extensive scour occurs. If the depth of the foundation is insufficient, the choice of abutment obviously is immaterial.

Another factor that contributed to damage was the location of abutments and piers in relation to the main river channel. During the field investigation, it was noted repeatedly that the amount of scour at bridge abutments and piers within the bridge opening depended primarily on the amount of constriction that the bridge opening imposed on the flood flow. Abutments and piers positioned near the edges of the main channel generally suffered extensive scour damage regardless of geometric shape or construction material unless they were protected by spur dikes or the approach embankments were constructed on a sufficiently low profile to provide relief as a result of overtopping.

The practice of locating an unprotected pier at the top of a riverbank should be avoided because a pier at this location is highly vulnerable to scour. If a pier must be constructed in this location, the pier shaft should extend well below the anticipated depth of scour. The outstanding performance of spur dikes during the June 1972 floods clearly demonstrated that they are one of the most effective means now available for preventing scour damage to bridge approaches, abutments, and adjacent piers in situations involving large quantities of overbank flow.

All 45 major bridges in Pennsylvania on the Susquehanna River and its major tributaries upstream from Harrisburg were checked to determine the cause of damage. Of this number only four were washed out or damaged to the extent that they had to be

Figure 21. Water-surface profiles of Chemung River for 1935, 1936, and 1946 floods.

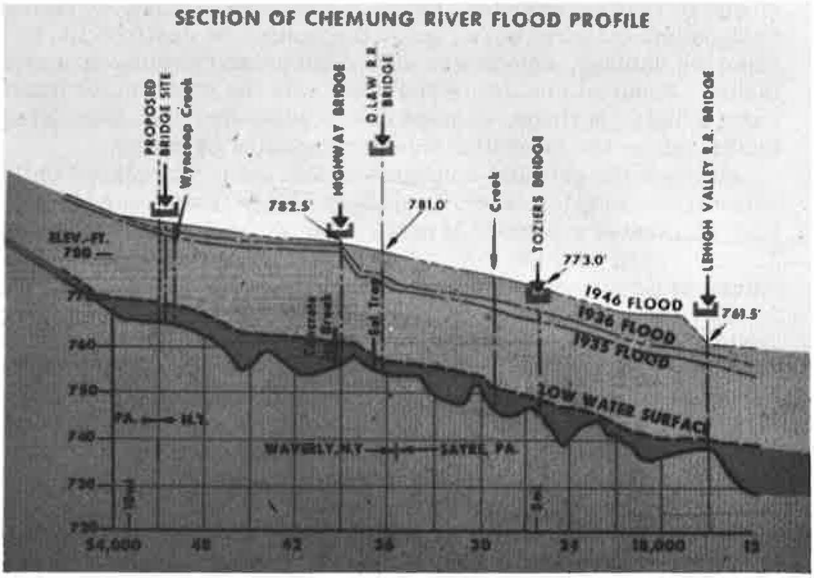

Figure 22. Undermined roadway slab and scoured embankment fill adjacent to Tioga River.

Figure 23. Cracked pier shaft supporting a county bridge on Schrader Branch of Towanda Creek.

Figure 24. Front view of cracked pier shaft and broken pier footing.

closed to traffic; however, many others were extensively damaged. (A total of 694 bridges and culverts were reported damaged or destroyed.) In virtually every case of reported damage, debris was either the primary cause or a significant contributing factor. Scour at abutments and piers was the other major cause of damage. Somewhat surprisingly, perhaps, damage due to superstructure inundation was not a significant factor unless the inundation was accompanied by debris.

Although the greatest emphasis in this study was placed on Pennsylvania's Susquehanna River bridges, several bridges in New York State were also included because they illustrated a number of noteworthy aspects of hydraulic and structural performance. In conjunction with the Pennsylvania structures they provided valuable insight into the nature of flood-induced bridge damage.

Only three bridges on the New York State highway system were reported completely washed out, but many others were severely damaged and required extensive repairs before they could be returned to full operation. [A total of 182 bridges were reported damaged or destroyed in New York State (1).] In addition, many county bridges were destroyed or badly damaged. Most of the damage was concentrated in the Genesee and Chemung River basins although other areas suffered major damage also. Debris and scour were the primary factors causing the damage—the same factors that caused the major damage in Pennsylvania.

If there was a common thread to the cause of the scour damage sustained by the bridges in Pennsylvania and New York, it could be characterized as follows: Any bridge site having an abrupt change in its cross-sectional waterway geometry, which forced floodwater to suddenly change its depth, distribution, or direction of flow, was potentially vulnerable to scour. This sudden but predictable change in a river's flood flow characteristics occurs naturally at the riverbank where the main channel joins the floodplain. Frequently, the abutments that frame the bridge opening are located there too. Often the worst scour conditions exist not at the peak of a flood but at an intermediate stage as the waters recede and the overbank flow returns to the main channel. Although scour frequently occurs in a random and unpredictable manner, a waterway constriction caused by a bridge opening in an embankment is usually most susceptible to damage in the vicinity of its abutments and piers, unless adequate scour protection is provided.

The location of the abutments and piers in relation to the main channel was an important factor in the damage that the bridges sustained. During the field investigations of the Susquehanna and Chemung River bridges it was noted repeatedly that the amount of scour at the abutments and in the bridge opening primarily depended on the amount of constriction that the bridge opening imposed on the flood flow. In general, abutments and piers that had been constructed at the tops of the riverbanks near the edges of the main channel sustained the greatest damage. This repetition of the damage pattern was prevalent, regardless of the shape of the abutments or piers and the material used in their construction. Exceptions were noted at sites where (a) spur dikes had been constructed at the abutments, (b) approach embankments had been constructed on a sufficiently low profile to provide adequate relief by means of overflow, and (c) a physical feature of the upstream floodplain had provided natural scour protection that was at least adequate for the conditions that had been experienced.

The following conclusions and recommendations were reached as a result of this study:

1. The primary causes of damage to bridges during the June 1972 flood were debris and scour.
2. In some instances, freeboard can help in reducing the damage inflicted by waterborne debris, but freeboard alone probably will not be effective in controlling debris damage when rare and unusual floods occur. Freeboard alone cannot guarantee the complete elimination of damage because the degree of protection is limited by the ever-present chance that a flood will occur that exceeds the level of protection provided by the freeboard, as well as by other engineering and economic considerations.
3. Bearing devices at piers of simply supported structures should be designed to resist dynamic flood forces, such as the horizontal forces due to impacting debris.

4. Structural continuity at bridge piers is a desirable structural feature because of the extra strength that this type of construction can provide.

5. Embankment or roadway overflow sections are recommended as a means of reducing potential debris damage at structures where heavy deposits of drift may accumulate, clog the bridge opening, and prevent use of the full capacity of the bridge waterway area. The relief provided by overflow reduces the pressure of the flowing water on the lodged debris, which in turn reduces the damage to the structure and the bridge opening. The risk of damage due to debris impacting a structure and clogging its waterway opening may be appreciably reduced because some of the drift can be conveyed through the overflow section and bypass the bridge.

6. Pile foundations for piers and abutments prevented many failures that would have occurred otherwise. According to the New York State DOT, spread footings constructed with adequate allowance for the depth of scour retained their supportive capacity also. Economic considerations might well be the deciding factor in determining which type of foundation to select in any given situation, but depth of foundation appeared to lessen the risk of failure from scour.

7. Scour at bridge abutments and within bridge openings primarily depends on the amount of constriction that the bridge opening imposes on the flood flow.

8. Piers located at the junction of the main channel and the floodplain are highly susceptible to scour. The practice of placing a pier in this location should be avoided, or more substantial provisions should be made for adequate scour protection.

9. Reliable water-surface profiles of rare floods are among the most relevant and useful items of hydrologic and hydraulic design information that can be obtained; their importance cannot be overemphasized. Bridge designers can use water-surface profiles to good advantage in a number of ways, and their use is recommended whenever possible. Although agencies such as the U.S. Geological Survey and the U.S. Army Corps of Engineers collect hydrologic and hydraulic data, state highway departments and railroads also record high-water marks from extreme floods.

10. Spur dikes were effective in controlling and preventing embankment scour behind and beneath bridge abutments and at adjacent piers even when the dikes were overtopped or partially destroyed. Their use is recommended wherever the transverse movement of a large overbank flow along a highway embankment toward a bridge opening is anticipated.

11. Highways that were designed for embankment overflow were effective in controlling scour at bridge abutments. Overflow sections might be a feasible alternative to spur dikes at some locations. Properly designed relief structures also can be used to maintain flow distribution and to reduce scour.

12. Downstream slopes of highway embankments that are designed for overflow may require protection from scour by paving, riprap, or some comparable type of ballasting if the anticipated drop between upstream and downstream water-surface elevations is large.

13. It is suggested that appropriate design committees, recommending design procedures and standards, consider incorporating provisions for accommodating highway-embankment overflow resulting from rare and unusual floods.

14. Bridges that had been designed and constructed in accordance with high structural and geometric design standards generally survived the flood in better condition than those that had been designed to a lower standard. However, the June 1972 floods clearly demonstrated that designing to such high standards alone will not be sufficient if essential hydrologic and hydraulic considerations are overlooked or if inadequate provisions are made to accommodate those considerations.

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