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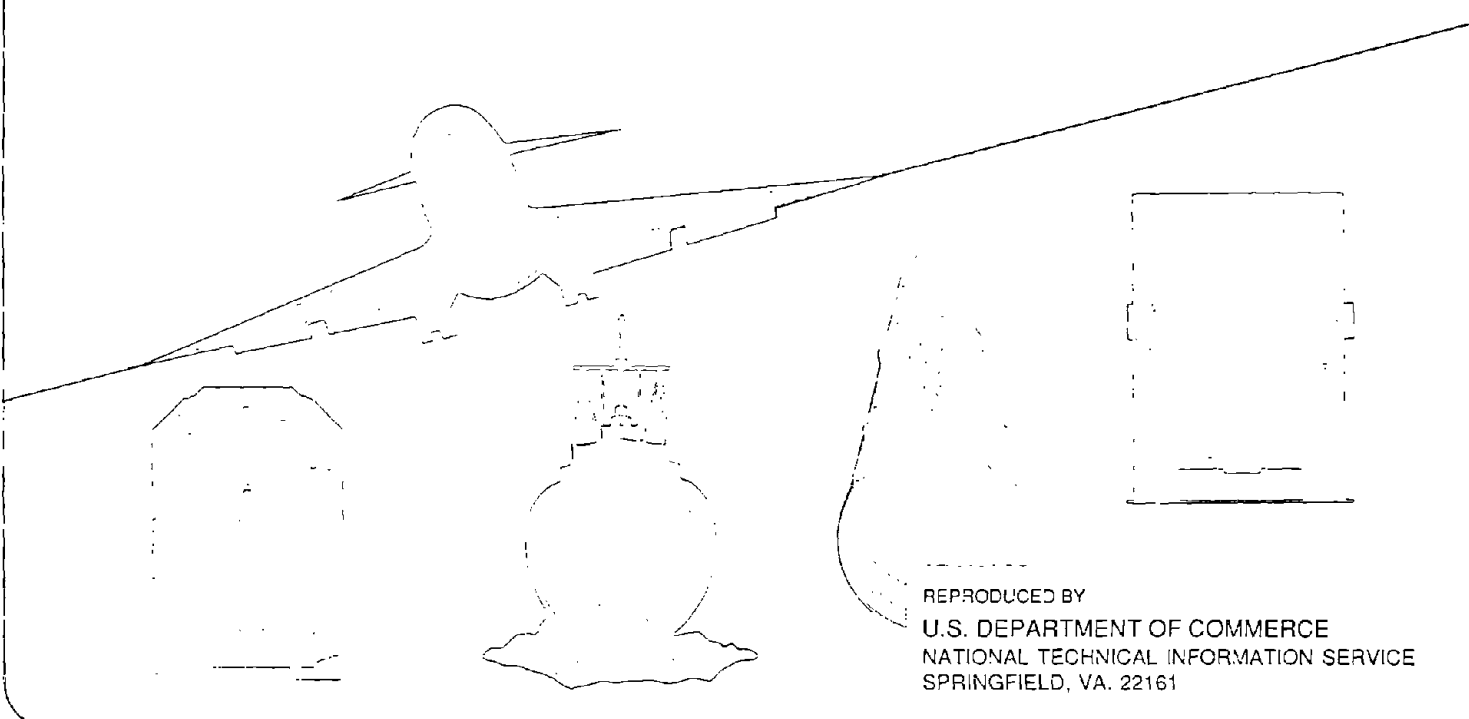


NTSB/HAR-90/01

NATIONAL
TRANSPORTATION
SAFETY
BOARD

HIGHWAY ACCIDENT REPORT

COLLAPSE OF THE
NORTHBOUND U.S. ROUTE 51 BRIDGE SPANS
OVER THE HATCHIE RIVER
NEAR COVINGTON, TENNESSEE
APRIL 1, 1989



REPRODUCED BY
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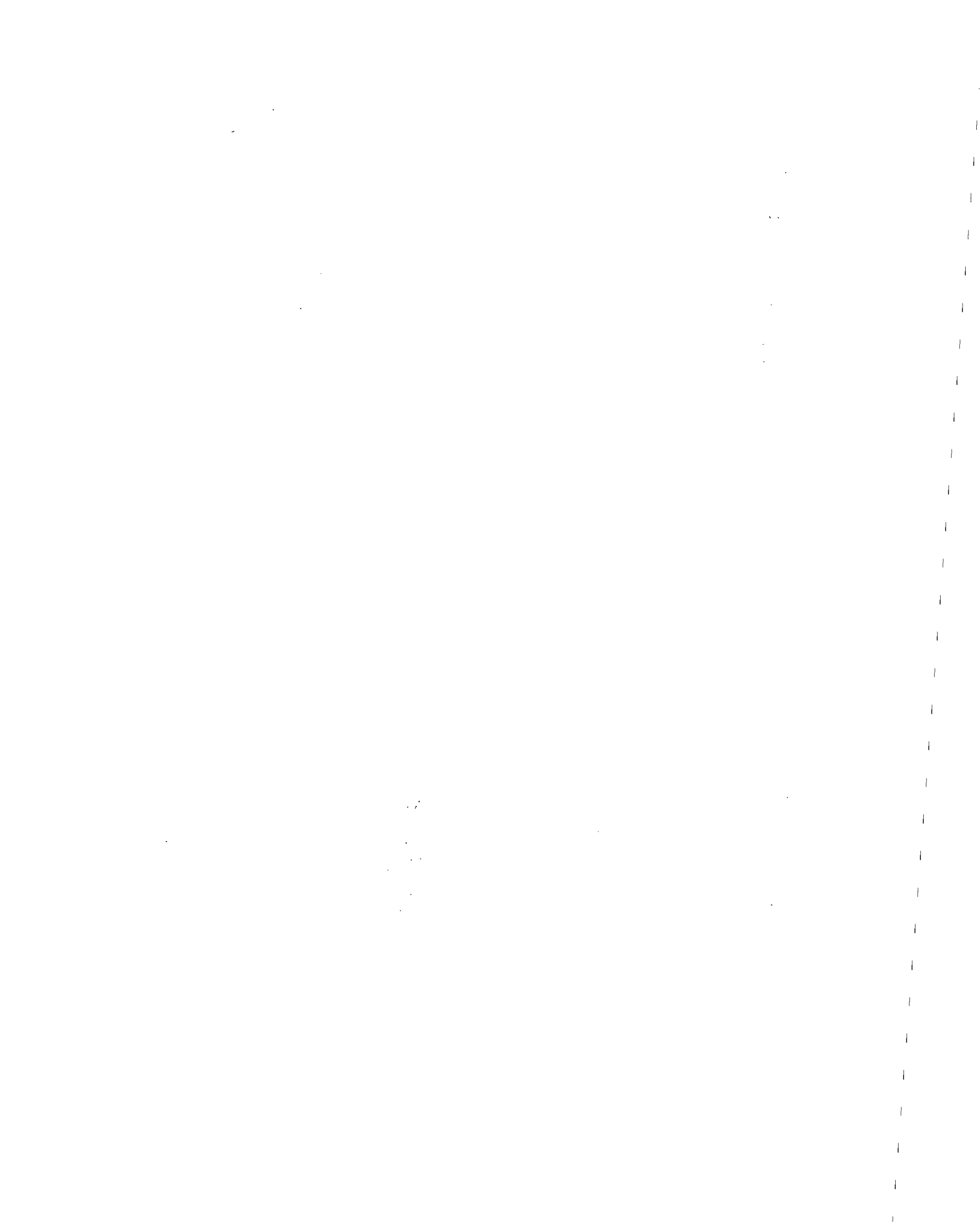
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16. Abstract This report explains the collapse of the northbound U.S. Route 51 bridge spans over the Hatchie River, near Covington, Tennessee, on April 1, 1989. The safety issues discussed in the report are the inspection procedures and the inspection report review procedures of the Tennessee Department of Transportation; bridge maintenance guidelines; overweight vehicle permit procedures; and Federal guidelines and standards for highway bridge inspection. Safety Recommendations addressing these issues were made to the Federal Highway Administration, the American Association of State Highway and Transportation Officials, the Tennessee Department of Transportation, and the State of Tennessee.			
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EXECUTIVE SUMMARY

About 8:15 p.m. c.s.t., April 1, 1989, an 85.5-foot-section of the 4,201-foot-long northbound U.S. Route 51 bridge over the Hatchie River fell about 20 feet into the 24-foot deep rain-swollen river after 2 pile supported column bents supporting 3 bridge spans collapsed. Witness reports and physical evidence indicate that the southern column bent (70) and the two spans that it supported fell quickly causing 4 passenger cars and 1 tractor-semitrailer to plunge into the river. The adjacent column bent (71) and the span that it was supporting, then collapsed on top of the vehicles. The river had apparently been at flood stage since November 1988. All eight vehicle occupants died as a result of the collapse.

The National Transportation Safety Board determines that the probable cause of the collapse of the northbound U.S. Route 51 Bridge spans was the northward migration of the main river channel which the Tennessee Department of transportation failed to evaluate and correct. Contributing to the severity of the accident was the lack of redundancy in the design of the bridge spans.

The primary safety issues raised by this accident are the adequacy of the Tennessee Department of Transportation (TDOT) inspection and inspection report review procedures; the adequacy of TDOT bridge maintenance guidelines; the adequacy of TDOT overweight vehicle permit procedures; and the adequacy of Federal guidelines and standards for highway bridge inspection.

Safety Recommendations addressing these issues were made to the Federal Highway Administration, the American Association of State Highway and Transportation Officials, the Tennessee Department of Transportation, and the State of Tennessee.

NATIONAL TRANSPORTATION SAFETY BOARD
WASHINGTON, D.C. 20594

HIGHWAY ACCIDENT REPORT

COLLAPSE OF THE NORTHBOUND U.S. ROUTE 51 BRIDGE
SPANS OVER THE HATCHIE RIVER,
NEAR COVINGTON, TENNESSEE
APRIL 1, 1989

INVESTIGATION

The Accident

About 7:14 p.m. central standard time, on April 1, 1989, traffic was moderate on the northbound U.S. Route 51 bridge over the Hatchie River near Covington, Tennessee. (See figure 1.) At that time, the Hatchie River was above flood stage, covering the flood plain with 3 to 4 feet of water, and the weather was cloudy and dry. A motorist traveling across the center of the bridge about 7:15 p.m. encountered a depression in the bridge deck, and stated that it felt as though her car had hit a large board in the road.¹ Later that evening, about 8:10 p.m., a motorist traveling about 50 mph across the bridge struck what she described as a "v" shaped depression in the deck just north of the center span, which nearly caused her to lose control of her vehicle. About 8:13 p.m., a motorist traveling about 55 mph over the center of the bridge crossed a "drop in the road," which caused the undercarriage of his truck to strike the bridge deck. About the same time, another motorist struck the depression in the deck causing him to strike his head on the vehicle's ceiling. This driver stated that the depression was about 2.5 to 3 feet deep.

About 8:15 p.m., another motorist stated that while traveling northbound across the bridge, he encountered a "3-foot" depression in the bridge deck, just north of the center span. After crossing this section of the bridge, the motorist observed two sets of vehicle headlights in his rearview mirror. He stated that the first vehicle traveled over the depression and continued northbound; however, the second vehicle disappeared from view. Following this observation, the motorist continued north about 3 miles to Henning, Tennessee to report the incident. Concurrently, a passenger car with 2 occupants was traveling northbound across the bridge. Both occupants stated that they encountered a deep depression in the bridge deck north of the center span, which caused them to strike their heads on the automobile's ceiling. After crossing the depression, they continued northbound for a short distance before stopping, and then observed a vehicle behind them fall into a void in the bridge deck where the depression had been. Simultaneously, they heard a loud "rumbling noise." Shortly afterwards they watched several more vehicles and a tractor-semitrailer drive into the void. These witnesses

¹This motorist reported her observations several days after the collapse.

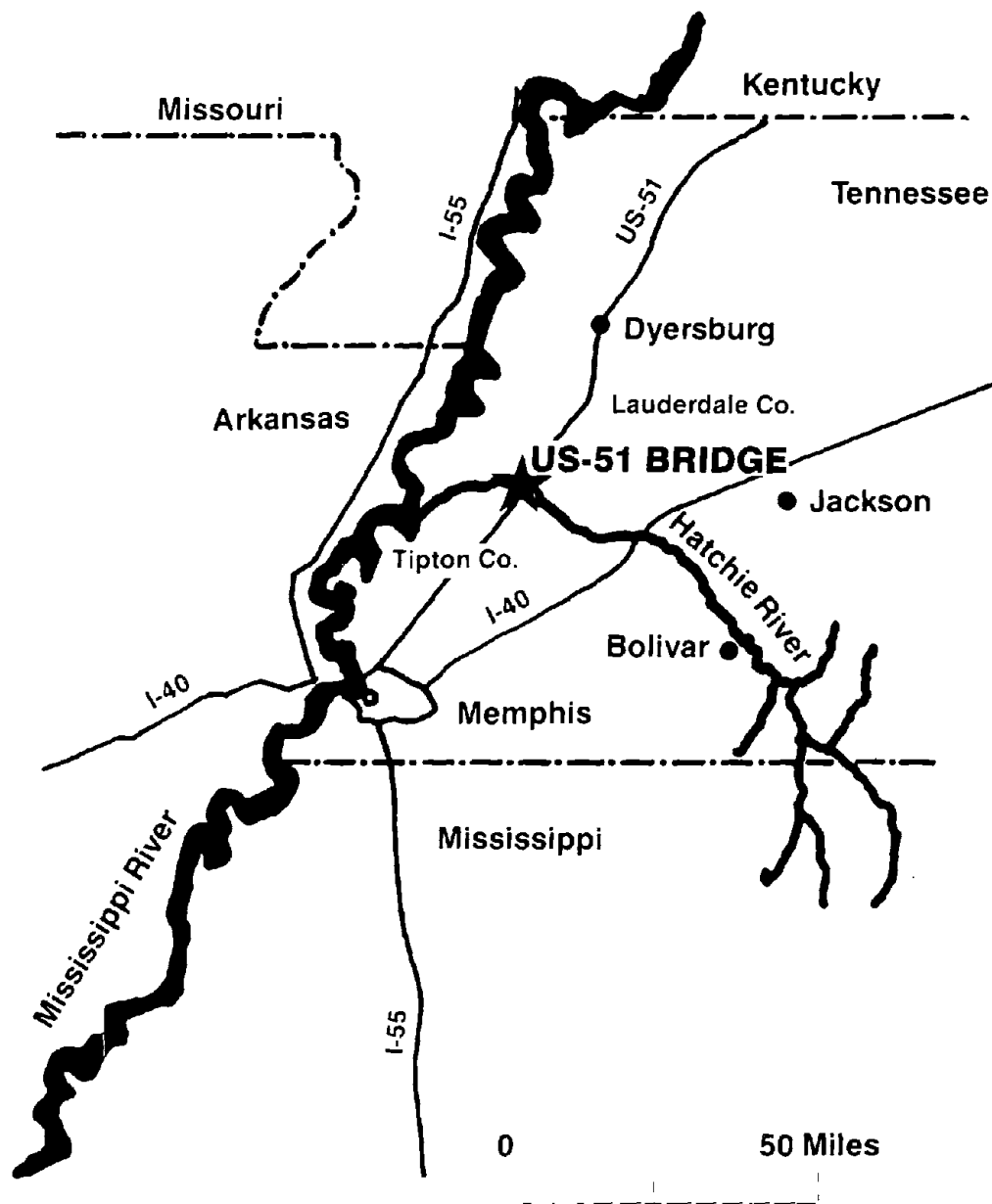


Figure 1.--Accident Location.

then drove about 1.5 miles to a rest stop north of the bridge and telephoned the Ripley, Tennessee Police Department to report the incident.

Also about 8:15 p.m., a driver and 2 passengers of a van were traveling about 50 to 55 mph northbound on the bridge. The driver stated that he was traveling in the right lane behind a tractor-semitrailer that was preceded by two automobiles. The van operator began to move to the left lane to pass when the truck suddenly moved into the left lane in front of the van. Several seconds later the van operator observed the tail lights of the trailer shift "from side to side, kick up in the air," and then disappear along with the two automobiles which were ahead of the truck. Following this observation, the van operator stopped his vehicle approximately 12 feet from the edge of the void. The operator and passengers exited the van, looked over the edge of the bridge, and observed the semitrailer floating in the river. The van occupants then proceeded south on foot and stopped oncoming traffic.

The Ripley Police Department was notified of a deep depression in the bridge deck at 8:19 p.m., and subsequently advised the Lauderdale County² Sheriff's Department which dispatched a sheriff's deputy to investigate the complaint. Shortly thereafter, both the Lauderdale and Tipton County Sheriff's Departments received several reports of the bridge collapse. Sheriff's deputies from both counties arrived at the bridge at 8:22 p.m. and discovered that a section of the bridge deck and the supporting column bents³ had fallen into the river. (See figure 2.) The deputies closed both ends of the northbound bridge, and from the bridge deck began to visually search the river with flashlights for victims or survivors. They were able to see one victim and the forward section of a 1978 Pontiac protruding from underneath one of the fallen spans, but did not observe any other victims or vehicles. The deputies made several attempts to reach the collapsed spans; however, due to debris and the depth of water on the flood plain they were unsuccessful. The Tennessee Highway Patrol (THP) and Covington Fire Department arrived at the bridge shortly after 8:30 p.m., and rescue personnel reached the collapsed spans several minutes later.

An underwater search of the river in the area of the collapsed spans conducted from April 1, to April 4, 1989, revealed that 4 passenger cars and one tractor-semitrailer with a total of 8 occupants had plunged into the river. All eight vehicle occupants died as a result of the collapse.

²The U.S. 51 Bridge connects Lauderdale County, Tennessee on the north side of the river with Tipton County, Tennessee on the south side.

³A column bent is a transverse support structure composed of two or more columns connected at their top most ends by a cap, strut, or other member holding them in their correct positions.

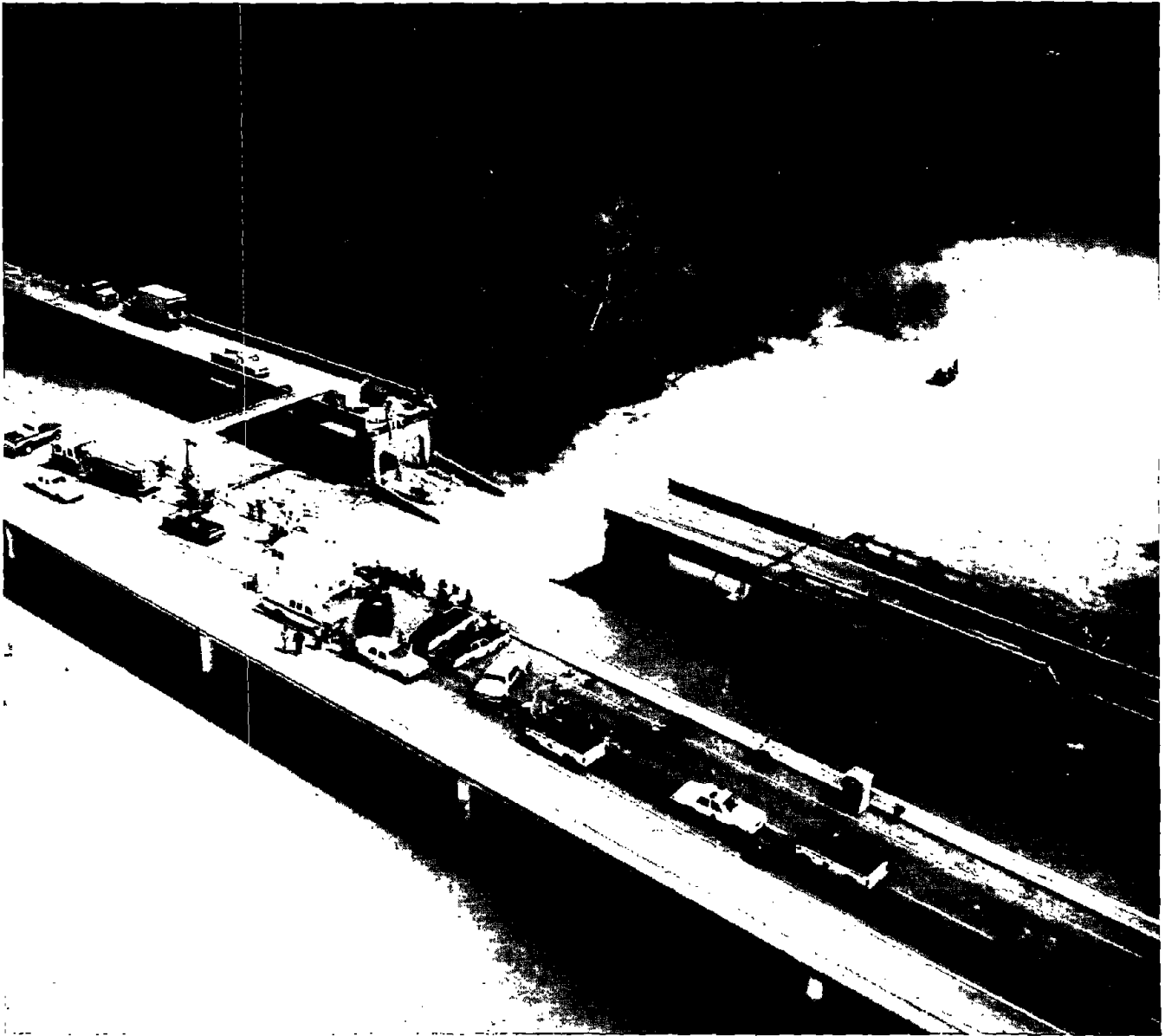


Figure 2.--View of the northbound U.S. 51 Bridge.
(looking northeast)

Injuries

	Drivers	Passengers	Total
Fatal ⁴	5 ⁵	3	8
Serious	0	0	0
Minor	0	0	0
None	0	0	0
Total	5	3	8

Vehicle and Occupant Information

Following the collapse, 3 of the passenger cars and the tractor were located underneath the northern-most collapsed bridge span. The passenger compartments of all these vehicles were severely crushed downward and exhibited some rearward deformation. Seven of the 8 victims were found within these vehicles, and post mortem examinations revealed that all had died as a result of massive head injuries. The fourth passenger car, a 1983 Dodge station wagon, was submerged in the main river channel, and was found adjacent to the west side of the bridge wreckage.⁶ This vehicle sustained a rearward displacement of the steering wheel and instrument panel, and crush damage to the front hood, windshield, and roof that extended into the passenger compartment. The eighth victim was found in the driver's seat of this vehicle. During the collapse sequence the semitrailer became separated from the tractor and floated about 200 yards downstream. It was located several weeks after the collapse.

Highway Information

U.S. Route 51 is a Federal-Aid Primary Highway that runs generally north-south from Ironwood, Wisconsin to New Orleans, Louisiana. About 6 miles northeast of Covington, Tennessee, U.S. 51 forms a rural 4-lane divided highway that spans the Hatchie River via two separate bridges. Prior to the bridge collapse, northbound traffic crossed the river over a 2-lane concrete bridge designed in 1931. Southbound traffic crossed the river over a parallel 2-lane concrete bridge designed in 1974, which was located 58 feet west of the northbound bridge. In 1988, the average daily traffic for each bridge was 5,730 vehicles. Single unit trucks⁷ accounted for 6 percent of the volume, while articulated trucks with 3 or more axles comprised 18 percent. The speed limit for both bridges was 55 mph.

⁴See Appendix B for pathological information.

⁵An external post mortem examination of one victim revealed that "multiple fractures and possible drowning" was the probable cause of death. However, the victim did not receive an internal post mortem examination.

⁶See Appendix B for further information concerning the post collapse location of the accident vehicles.

⁷These included buses, panel trucks, and other 3 or 4-axle single unit trucks.

Bridge Information

General Description of the Northbound Bridge.--The northbound U.S. 51 Bridge, designed by the State of Tennessee Department of Highways and Public Works (TDHPW) in 1931, was opened for traffic in 1936. The 4,201-foot-long bridge was constructed to span the main channel of the Hatchie River, and a majority of the river flood plain. The bridge consisted of 143 spans supported by 2 concrete abutments, 117 concrete pile bents⁸, 18 pile-supported concrete column bents, and 7 pile-supported concrete piers.⁹ The pile and column bents were numbered from south to north, 1 to 135, and the piers were numbered from south to north 1 through 7.

Superstructure.--The superstructure was designed with 137 (28.5 foot long) simply-supported spans¹⁰ extending across the flood plain, 5 (43-foot long) simply-supported spans extending across the main channel, and an 81.5-foot-long pony truss¹¹ center span. The flood plain spans consisted of 5 longitudinal reinforced concrete T-beam¹² girders that were 14 inches wide and 21 to 22 inches tall. The girders were constructed with 2 layers of 1.0 to 1.25-inch square steel reinforcing bars (rebars) placed longitudinally in the bottom of the beam stems. Stirrups¹³ were spaced transversely throughout the girders at 6 to 11-inch intervals, and reinforced concrete diaphragms¹⁴ joined the girders together at both ends of each span. The spans were fixed to the substructure at one end, were equipped with expansion

⁸A pile bent is a transverse support structure composed of piles and a pile cap.

⁹A pier is a transverse support structure constructed in a solid shaft or block-like configuration.

¹⁰A superstructure span designed to be unaffected by stress transmission to or from an adjacent span. See appendix F for further details.

¹¹A jointed structure having an open built web construction so arranged that the frame is divided into a series of triangular figures with its component straight members primarily stressed axially only.

¹²A reinforced concrete T-beam derives its name from a similarity of shape to the letter "T", the head or topmost element of the beam comprises a portion of the deck slab which is constructed integrally with the beam stem.

¹³A stirrup is a U-shaped steel rod, bar or angle piece providing support for a bridge girder.

¹⁴A diaphragm is a reinforcing member placed within a bridge deck system to distribute stresses and improve strength and rigidity.

plates¹⁵ at the opposing end, and were separated from each other by bituminous felt expansion joints. The main channel spans were equipped with expansion rollers¹⁶ and consisted of 4 concrete T-beam girders that were 18 inches wide and 32 inches tall; otherwise, they were similar to the flood plain spans. The pony truss was equipped with expansion rockers.¹⁷

The girders and pony truss supported a 24-foot-wide, 8 to 10.5-inch-thick reinforced concrete deck that was covered by a thin asphalt overlay. On each side of the deck, a 33-inch-tall concrete masonry bridge rail was attached to a 9-inch-high curb. Alignment of the bridge deck was straight and the roadway had a parabolic crown¹⁸ for drainage with a maximum 1.5-inch drop from the center to the curb. Additionally, the pony truss was at the center of a 400-foot radius vertical curve that had a maximum 2.39 percent positive grade. (See figure 3.)

Substructure.--The peripheral flood plain spans were supported by concrete pile bents (1 through 59, and 78 through 135). These pile bents were comprised of a 24-foot-long, 2.5-foot-deep, and 2.83-foot-wide reinforced concrete bent caps supported by five 30 to 39-foot-long precast concrete piles driven to an elevation of about 230 feet.¹⁹

The flood plain spans closer to the main channel were supported by concrete column bents (60 through 69, and 70 through 77). According to the design plans, these column bents consisted of a 24-foot-long, 4-foot-tall, and 2.83-foot-wide reinforced concrete bent cap supported by two 2 foot-square, 27-foot-tall reinforced concrete columns. Each column was supported by a 6.5-foot-square, 3-foot-deep reinforced concrete footing resting on

¹⁵Two fixed steel plates separated by a copper plate designed to transmit longitudinal movement of the span resulting from temperature changes and superimposed loads.

¹⁶A cylinder so mounted that by revolution it facilitates the longitudinal movement of the span resulting from temperature changes and superimposed loads.

¹⁷A cylindrical, sector-shaped member attached by a pin or trunnion at its axis location to the truss and having a line bearing contact upon its perimetral surface with a plate or pedestal, thus providing for the longitudinal movement of the truss resulting from temperature changes and superimposed loads.

¹⁸A parabolic crown is an element of the highway cross section created by raising the roadway centerline above its edges.

¹⁹Elevations in this report are relative to the National Geodetic Vertical Datum of 1929, generally referred to as "sea level." The average flood plain elevation at the bridge site was about 250 feet.

five 20-foot-long untreated timber friction²⁰ piles. Typically, each column bent cap was designed to be reinforced near the top with two 0.5-inch square rebars, and near the base with seven 1-inch square longitudinal rebars and six 0.75-inch rebars that extended diagonally into the columns. The columns were reinforced with eight vertical 0.625-inch rebars wrapped by 0.25-inch rebars at 1-foot intervals. The bridge design plans indicated that the concrete footing was tapered and was reinforced with four overlapping layers of 0.625-inch square rebars. The untreated timber piles were embedded 1-foot in the concrete footing and arranged vertically with one pile in the center, and one pile located 1.5 feet from each corner of the footing. The design plans also indicated that the butt ends²¹ of the timber piles at column bent 70 and 71 (the collapsed column bents) were located at elevation 238.90 and 238.47 feet, respectively, and the tip ends were located at elevation 218.9 and 218.47 feet, respectively. (See figure 4.)

According to the design plans, the main channel spans were supported by reinforced concrete piers 1 through 7. Piers 1, 2, 3, 4, and 7 were 44.6 to 46.6 feet tall, 26 to 30 feet long, and 2.83 to 7 feet wide and were supported by twenty-nine 20-foot-long untreated timber piles. The piles were embedded in the concrete piers about 1 foot at an elevation of 224.5 feet. The pony truss was also supported by reinforced concrete piers 5 and 6, which rested on thirty eight 20-foot-long precast concrete piles. These concrete piers were similar but slightly larger than the piers supporting the main channel spans.

Design Guidelines Applicable to the Northbound Bridge.--According to the design plans, the northbound bridge was designed to conform with the 193.1 TDHPW bridge construction specifications.²² These specifications indicated that 20-foot-long untreated timber piles were to be at least 11 inches in diameter 4 feet from the butt end, and no less than 8 inches in diameter at the tip end. Although the TDHPW specifications mainly discussed materials composition and construction procedures, they did indicate that bridge support structures should be constructed parallel to the waterway. The specifications did not address the need for hydraulic evaluations in conjunction with bridge design. The design load used for this bridge consisted of 2 adjacent 15-ton 2-axle trucks with a 14-foot wheelbase and 80 percent of the weight carried on the rear axle.

²⁰A pile which receives its support through friction resistance between the surrounding soil and the surface of the pile.

²¹Due to the natural taper of timber piles, the butt end, which is generally embedded in the pile cap or footing, is larger in diameter than the tip end, which is generally embedded in the streambed.

²²Standard Specifications for Road and Bridge Construction, Tennessee Department of Highways and Public Works, Nashville, TN, October, 1931.

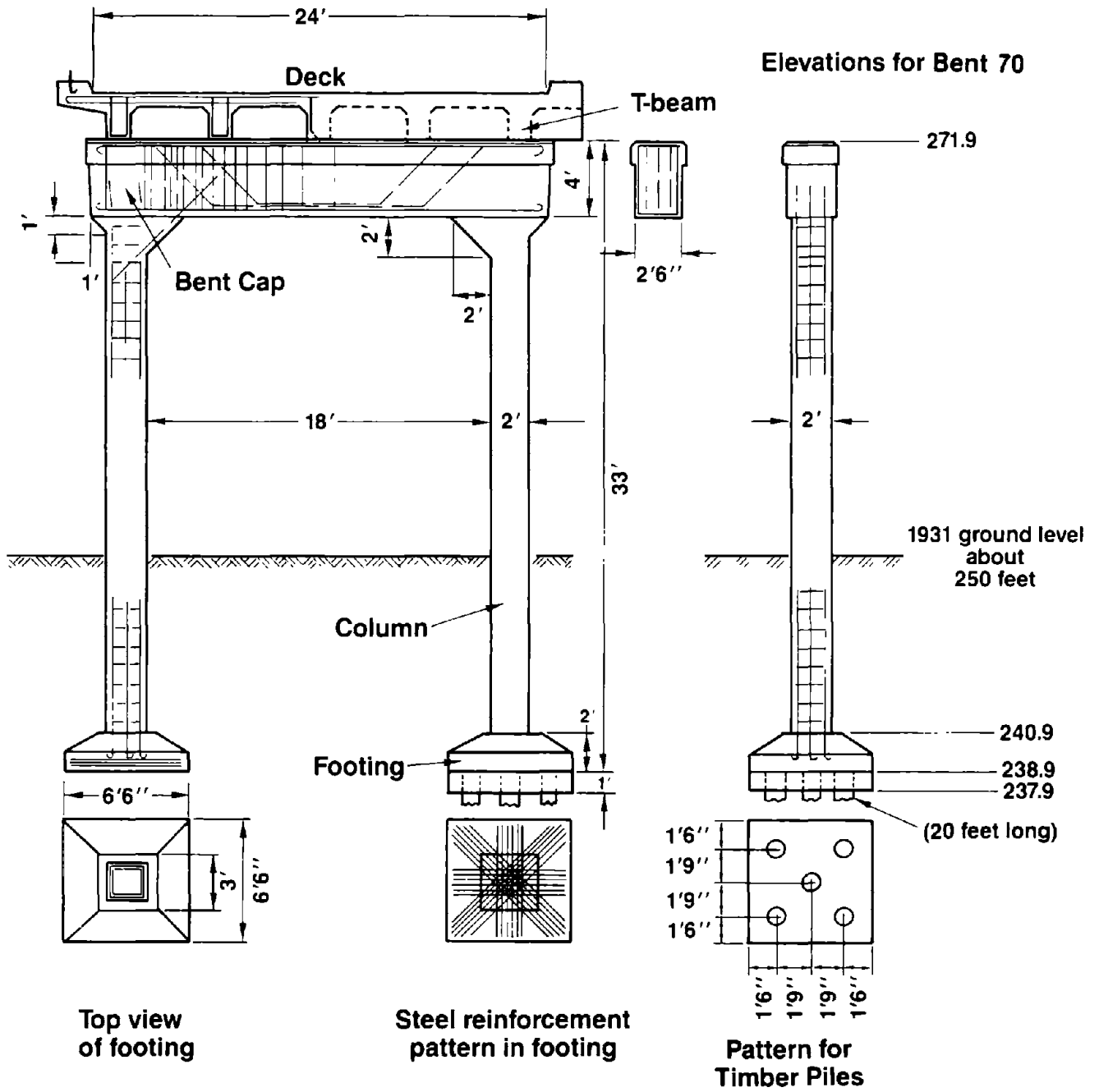


Figure 4.--Column bent 70 cross section.

General Description of Bridge Damage.--During the collapse, spans 77, and 78 (spans are numbered from south to north 1 to 143, the truss span was 75) and both column bents (70 and 71) fell beneath the surface of the river. Further, span 79 fell against column bent 72 and became partially submerged. Following the collapse, rescue workers demolished span 79 to recover the victims and vehicles trapped underneath the span. Prior to its demolition, this span appeared to be intact. Rescue workers also removed the west column of column bent 71, which was located underneath span 79, and on top of the tractor wreckage.

On April 7, 1989, following the recovery of the accident vehicles, the Safety Board, in cooperation with the Federal Highway Administration (FHWA), arranged for Collins Engineers Inc. (CEI) to document and examine the submerged segments of the bridge wreckage. Because of the limited visibility²³ at the time and the swift flood water current, CEI divers were unable to fully examine the upstream sides of span 77 and 78, or the area underneath the spans. Therefore, on August 17, 1989, the Safety Board had CEI perform a second examination of the submerged bridge wreckage during a non-flood period.²⁴

Superstructure Wreckage Documentation.--The underwater examinations of the bridge wreckage indicated that spans 77 and 78 fell almost in line and slightly west of their original positions. (See figure 5.) The exterior girders of both spans appeared to be intact. CEI reported that they found only minor broken concrete on the girder ends that would have rested on column bent 70, and no significant distress in the girders. The concrete bridge railing of both spans was irregularly broken near column bent 70, and divers discovered trees lodged underneath the upstream bridge rail near the center of span 77. The southern end of span 77 was leaning against pier 7 about 12 feet above the streambed. Span 78 and the northern end of span 77 were resting on both the streambed and portions of the substructure wreckage. The deck of both spans appeared to be intact with partial delamination of the asphalt overlay.

Substructure Wreckage Documentation.--The underwater examinations of the substructure wreckage indicated that column bent 70 came to rest on its northern side, partially buried in the streambed underneath spans 77 and 78. The columns were positioned perpendicular to the river, and were separated from the footings. The footings and lower half of the columns were located south of the pre-collapse centerline of the column bent, while the remainder of the columns and the bent cap were located north of this position. (See figure 6.) Because of the wreckage distribution, CEI divers were unable to examine the majority of the bent cap. Divers did examine about 4 feet of the bent cap's west side which appeared to be intact and connected to the west column. The lower portion of the west column was

²³Due to limited visibility, CEI divers conducted their examination of the bridge wreckage by touching each bridge element.

²⁴During this examination, CEI divers indicated that visibility was 6 inches to 1-foot except near the streambed where the visibility was zero.

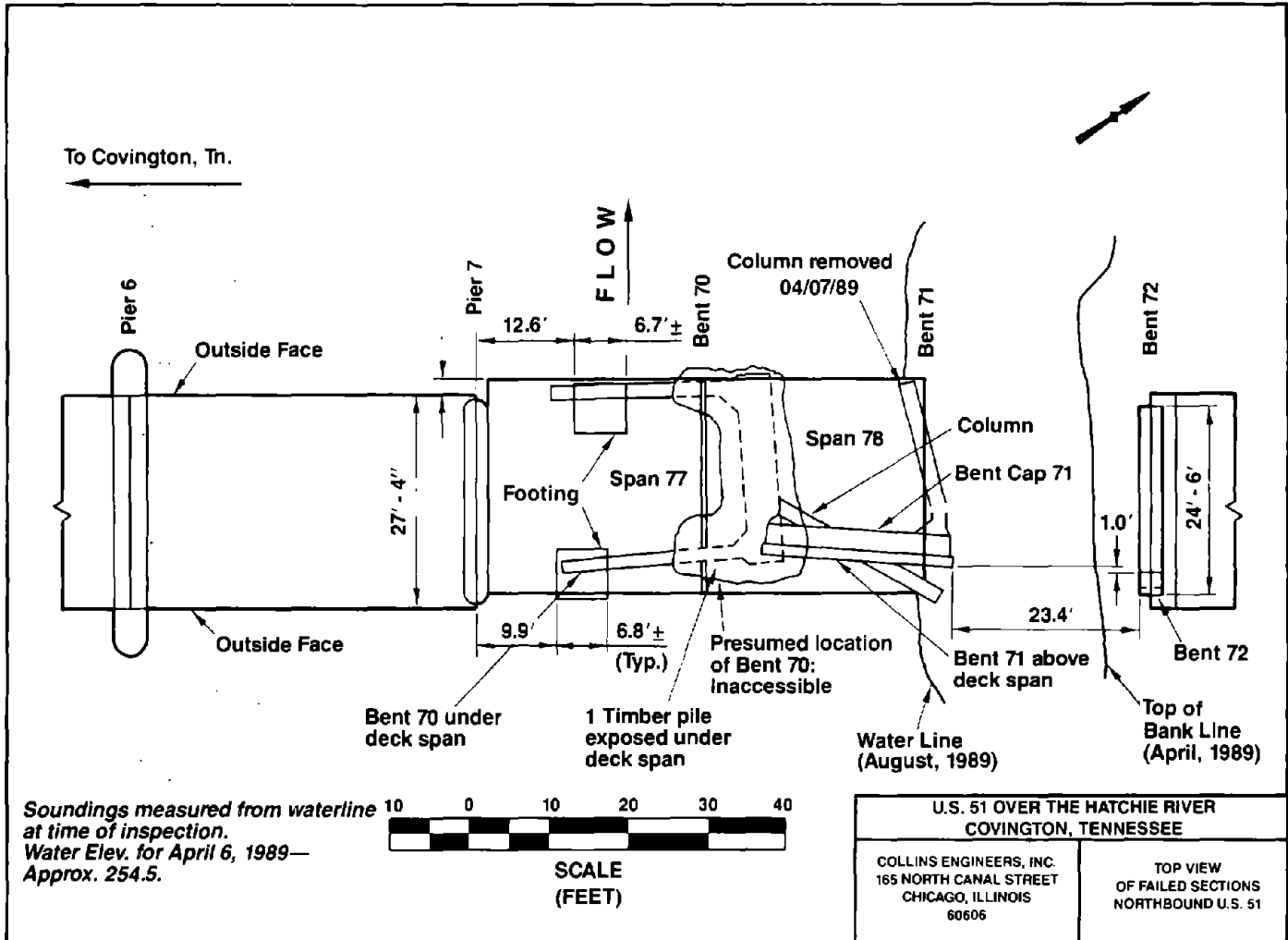


Figure 5— Wreckage Distribution-Top View

Figure 5.--Wreckage Distribution-Top View

located under the span 77 deck, adjacent to the west exterior girder. The column had a fairly smooth fracture near its base with 3 broken rebars protruding slightly from the fractured area. The lower end of the column was located about 12.5 feet north of pier 7. The east column was located underneath the east exterior girders of both spans. The column was fractured directly beneath the convergence of the submerged spans and also near its base. The fracture near the column base was irregular and a small 1-inch-wide section of the footing remained attached to the west side of the column. Additionally, a 1-foot-long broken rebar protruded from the fractured base and was bent backward along the northwest side of the column. The base of the east column was located about 10 feet north of pier 7.

The east footing of column bent 70 was located about 9.9 feet north of pier 7 and was resting partially on the streambed and partially on timber pile debris and trees. CEI divers reported that the concrete footing was about 3 feet thick, was not tapered as the design plans had indicated, and had 3 broken rebars extending from the top of the footing about 2 to 6 inches. The divers were able to reach under the north and east sides of the footing and indicated that the bottom of the footing had an irregular surface "as would be expected if the concrete were placed on soil." The divers also examined remnants of the 2 northern piles embedded in the footing. The northeastern pile was about 11 inches in diameter and was irregularly fractured about 2 inches below the footing. The northwestern pile was fractured about 10 inches below the footing. The west footing was located about 12.6 feet north of pier 7 and was also resting partially on the streambed and on debris. This footing was essentially in the same condition as the east footing. CEI divers were only able to examine the southeastern pile which was irregularly fractured just below the footing.

Further, CEI divers discovered remnants of a timber pile extending about 3 inches to 1-foot above the streambed in the area where the east footing of column bent 70 had been originally located. The divers indicated that the pile had split below the streambed, and stated that the pile "appeared to be sound... the diver could not break off a piece by hand."

CEI divers and Safety Board investigators also examined the wreckage of column bent 71 which was located on top of span 78. The bent cap was positioned perpendicular to the river near the east side of span 78, and exhibited some minor concrete deterioration near the bottom, but otherwise appeared to be intact. Red paint marks were located on the south side of the bent cap about 8 to 10 feet from the west end. Gray or light green paint marks were located on the south side of the bent cap near the west end and also about 10 to 15 feet from the west end. Prior to its removal by rescue personnel, the west column was positioned nearly parallel to the river resting on its northern side. The column was fractured and shattered near the bent cap, and two damaged 1.5 to 2-foot pieces of concrete were attached by rebars to the lower section of the column. Below this fracture, a 3-foot-long segment of the column's east side was chipped and crushed. Further, the column had a fairly smooth fracture near its base with several necked down rebars extending 0.5 to 3 inches from the fractured area. The east column was located underneath the bent cap and was positioned in a northeasterly

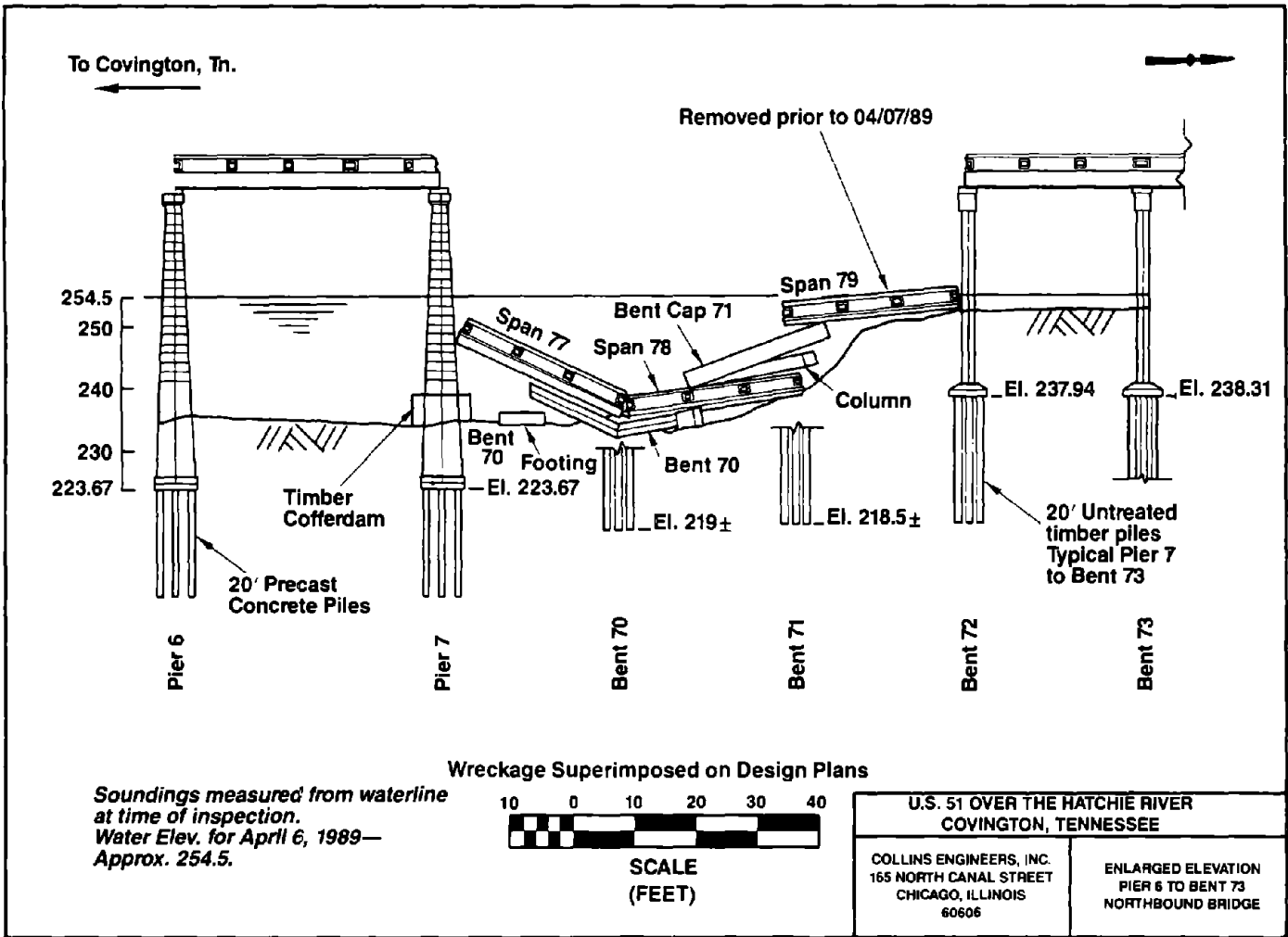


Figure 6 — Wreckage Distribution Side View.

Figure 6.--Wreckage Side View

attitude, resting on its northern side. The column was fractured near the bent cap, and divers found rebars that had been bent backwards, connecting both elements. Further, the column was fractured near its base with broken rebars extending 1 to 2 inches from the fractured area. CEI divers were unable to locate the footings or piles of column bent 71. The divers indicated that these sections may have been buried in the northern bank.

An examination of the bridge members adjacent to the submerged wreckage revealed that column bent 72 was leaning 1.8 to 3 degrees north of its original position, and that the south sides of both concrete columns were scraped. (See figure 7.) CEI divers discovered the remnants of a timber cofferdam²⁵ surrounding pier 7 (See figure 8.) that extended about 7 feet above the streambed and about 2 feet from the pier. Further, two separate tiremarks were located on the asphalt deck of the truss span and span 76. The most pronounced tiremark was a dual skidmark that began near the center of the roadway on the truss span, and continued slightly leftward for about 100 feet to the north edge of span 76. Additionally, a single tiremark extended from the center of the roadway leftward about 15 feet to the north edge of span 76.

General Description of the Southbound Bridge.--The southbound U.S. 51 bridge was designed and funded by the Tennessee Department of Transportation (TDOT) in 1974 and was opened for traffic in 1976. The 999-foot-long bridge was designed to span the main channel of the Hatchie River. It consisted of 13 reinforced concrete spans supported by 2 reinforced concrete abutments, and 12 reinforced concrete column bents. Each column bent was supported by 6 precast concrete piles. The approach roadway to the bridge was constructed on top of earthen embankments positioned across the flood plain on both sides of the main channel. Additionally, 100-foot-long earthen spur dikes²⁶ covered with stone riprap²⁷ were constructed adjacent to the upstream side of each abutment. These spur dikes were situated parallel to the river and extended underneath the northbound bridge.

²⁵A cofferdam is an open box-like structure constructed to surround the area to be occupied by a pier to permit dewatering of the enclosure so that the excavation for the preparation of a foundation may be effected in the open air.

²⁶A spur dike is a projecting jetty-like embankment placed adjacent to an abutment to secure a gradual contraction of the stream width and induce a free even flow of water adjacent to and beneath a bridge.

²⁷Riprap is stone or a similar protective covering material deposited on the beds and banks of rivers and streams to prevent erosion and scour by water flow.

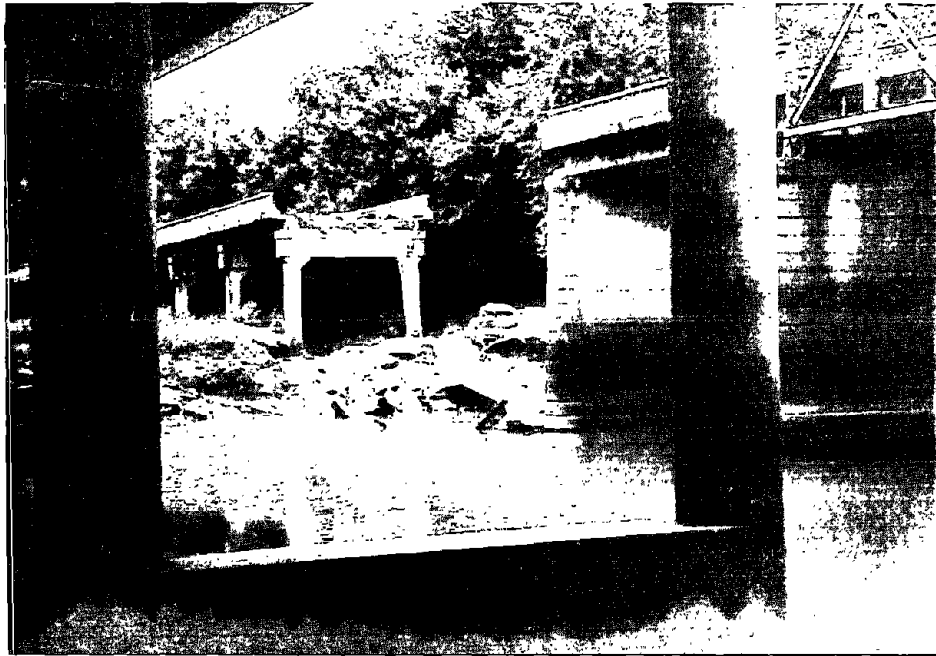


Figure 7.--Column bent 72.



Figure 8.--Pier 7.

Design Considerations and Guidelines Applicable to the Southbound Bridge.--Design plans indicated that TDOT utilized the 1973 American Association of State Highway Officials (AASHO)²⁸ standard bridge specifications²⁹ when designing and constructing the southbound bridge. These specifications indicated that when selecting bridge locations; "Natural stream meanders should be studied and if necessary, channel changes, river training works and other construction which would reduce erosion problems and prevent possible loss of the structure should be considered." The specifications further stated that to determine adequate waterway openings, "Hydraulic studies of bridge sites are a necessary part of the preliminary design of a bridge and reports of such studies should include applicable parts of the following outline:... 2. Complete data on existing bridges, including dates of construction and performance during past floods... 4. Information on ice, debris and channel stability."

In December 1972, TDOT requested that the U.S. Geological Survey (USGS) perform a preliminary hydraulic study of the Hatchie River at the U.S. Route 51 crossing. The purpose of this study was to establish the minimum opening needed for a new bridge. A summary of the study indicated that the maximum known flood at the site occurred in January 1937 with an estimated discharge of 65,000 cubic feet per second (cfs), and a mean velocity of about 1.2 feet per second (fps). The study concluded that an 840-foot-long bridge would provide sufficient area to carry a 65,000 cfs flood at a mean velocity of 5 fps.

In March 1974, following the development of the 999-foot-long bridge design, TDOT requested the USGS to perform a second hydraulic study of the Hatchie River. The purpose of this study was to establish the backwater effects the bridge would create during flood conditions. The study concluded that:

"The site is subject to flooding both by head-water floods and by [static] backwater floods from the Mississippi River... The proposed constriction will cause backwater on the upstream side of the embankment. Backwater due to constriction; however, will be greatest when the mean velocity through the opening is the highest which is during a period of no [static] backwater. Computations indicate that the proposed bridge between stations 268+50 and 278+50 will cause about one foot of backwater during a flood equal to the one in 1937... It should be pointed out; however,

²⁸Now the American Association of State Highway and Transportation Officials.

²⁹American Association of State Highway Officials, Standard Specifications for Highway Bridges, eleventh edition. AASHO, Washington, D.C., 1973.

that the existing highway is also causing some backwater so the net effect of the proposed highway would be almost insignificant."

TDOT engineers indicated that they utilized the information from both USGS studies and determined that the maximum scour depth that would occur with a 5 fps flow was 2 feet around the flood plain column bents, and 19 feet around the main channel column bents. TDOT also determined that spur dikes were needed to align the flow through the southbound bridge opening and that the bridge could withstand a 100-year recurring 80,000 cfs flood.

Meteorological and Flood Information

Meteorological Information.--On the day of the collapse, the weather in the Covington, Tennessee area was generally cloudy and dry. A review of the historical weather data for the area revealed that 4.09 inches of rain fell during the 15-day period preceding the collapse, with one heavy rainfall of 2.32 inches occurring on March 29, 1989. The 30-year average rainfall for this 15-day period was 2.65 inches. From November 1, 1988 to April 1, 1989, the Covington area received 40.39 inches of rain which was 78 percent greater than the 23.4-inch 30-year average rainfall for this period.

Flood Frequency and Duration.--From 1936 until the day of the collapse, the U.S. Army Corps of Engineers (COE) maintained a water monitoring gauge located on the downstream side of pier 6 of the northbound bridge. Data collected from this gauge indicated that the Hatchie River had continuously been well above its average daily discharge³⁰ rate of 2,600 cfs from November 20, 1988 (9,750 cfs), until the time of the collapse on April 1, 1989 (8,620 cfs). The maximum discharge for this period, 28,700 cfs, occurred on January 19, 1989, and the discharge rates for the three months preceding the collapse were:

January 1989:	maximum-28,700 cfs minimum-7,050 cfs mean-13,300 cfs
February 1989:	maximum-23,500 cfs minimum-4,300 cfs mean-11,700 cfs
March 1989:	maximum-13,900 cfs minimum-3,070 cfs mean-8,590 cfs

Following the collapse, the USGS performed a flood frequency analysis of the Hatchie River in the area of the U.S. 51 Bridges utilizing data from the COE gauge from 1940 through 1989. The maximum flood during this period (55,700 cfs) occurred in 1946. The USGS study indicated that the

³⁰Discharge is the volume rate of flow of the water including any sediment or other solids that may be dissolved or mixed with it.

Hatchie River experienced an annually recurring flood season³¹ that generally lasted from November to April. According to the USGS study, "The magnitude of the flood peak for the 1989 flood season was not extraordinary: 28,700 cfs". The USGS determined that this was a 3-year recurring flood. The USGS analyzed the mean daily flow data for November through March, during the years 1940 through 1989. This analysis indicated that although the 1989 flood season did not have consistently high ranking peaks, each month had sustained "out-of-bank" flows.

The USGS also compared flow-durations for the Hatchie River for the period prior to the construction of the southbound bridge (1940 to 1974), with flow-durations for the period after the bridge was constructed (1976 to 1989). Additionally, the USGS compared these data periods with the total flow-durations (1940 to 1989). The USGS indicated that these periods showed only slight gross flow-duration differences, except at the extremely high discharges. However, data did indicate that the 1989 flood season ranked in the top ten of all flood seasons for sustained out-of-bank flows. Further, the USGS considered the entire 1989 flood season to be the most severe since the construction of the southbound bridge. Data indicated that 3 out of the 5 months of the 1989 flood season had the highest mean-discharge rates since 1975.

Hatchie River Channel Evolution

The Hatchie River originates near Alpine, Mississippi and flows northwest through western Tennessee to the Mississippi River. The river is characterized as a naturally sinuous, meandering channel, that has a broad flood plain ranging from 1.5 to 2.5 miles wide. The Hatchie River maintains a low channel gradient³² (0.0001 feet/foot), substantially vegetated banks, and a generally stable bed. According to the COE, the Hatchie River is one of the few large rivers in west Tennessee that has not been subjected to large-scale dredging or channel straightening. The only widespread artificial alterations of this river was some snagging of submerged debris between 1938 and 1943, and again between 1945 and 1952.³³

At the U.S Route 51 Bridge site, the Hatchie River flood plain is about 7,200 feet wide between 264 foot elevation contours. The area is thickly wooded except for the downstream north flood plain that was cleared for agriculture sometime after 1979. Approximately 1,000 feet upstream from the northbound bridge, the main channel forms about a 90-degree left bend. The river flows westerly through the bridge site in a generally straight path and then bends leftward about 1,000 feet downstream of the southbound bridge.

³¹ A flood season consists of the period when a river begins to rise and stays at flood elevation for an extended period.

³²The descending or ascending slope of a streambed.

³³Robbins, Clarence H. and Simon, Andrew, 1983, Man-induced Channel Adjustments in Tennessee Streams: U.S. Geological Survey Water-Resources Investigations Report 82-4098, 96 p.

At the time of the collapse, the average flood plain elevation was about 250 feet, and the average elevation of the river's main channel was about 233 feet. (See figure 9.)

Following the collapse, the Safety Board, in cooperation with the TDOT, arranged for the USGS to conduct a channel evolution study of the Hatchie River reach from about 1,000 feet upstream to about 1,000 feet downstream of the U.S. 51 Bridges. The purpose of the study was to describe the evolution of cross section and channel characteristics, and the evolution of velocity and discharge distributions near the bridges. Data collected from the COE monitoring gauge was used in this study. Additionally, aerial photographs of the river at the bridge site were retrieved from the COE and examined.

Further, the Safety Board and FHWA directed CEI to conduct an underwater inspection shortly after the collapse to determine the condition of the Hatchie River streambed at the northbound bridge site. This inspection included soundings of the river bottom, and sub-bottom profiling.

Channel Migration.--Between 1931 and 1934, the TDHPW straightened the main channel of the Hatchie River at the site of the soon-to-be-constructed northbound U.S. 51 bridge. According to the 1931 bridge design plans, this was done to allow the river flow to approach the bridge at a perpendicular attitude. A leftward bend in the river was straightened and the main channel was moved about 124 feet northward. The new channel bed elevation was set at 232 feet and "constructed to accommodate the previous channel volume." The bridge was constructed so that the geometric center of the straightened channel was midway between Piers 5 and 6, the top of the north bank was situated just south of pier 7 at an elevation of about 248 feet, and the top of the south bank was at elevation 245 feet. Based on the 1944 to 1989 COE cross-section datum, there are indications that portions of the old natural channel were not completely filled following the construction of the new channel.

In 1944, the elevation of the south bank was lowered from about 248 feet in 1931, to about 243 feet. However, the north bank and flood plain had increased about 1 to 3 feet in elevation and the south flood plain had increased about 1 to 4 feet in elevation. The USGS attributed this elevation change to sediment and debris deposits on the flood plain from floods. The main channel thalweg³⁴ had aggraded about 2.5 feet to an elevation of about 235 feet. Also, the top of the north bank had moved northward about 22 feet and was located north of pier 7.

By January 1973, the old natural channel had filled in and the top of the south bank was located just south of pier 5. In 1973, the south flood plain elevation had increased to about 248 feet. The majority of the main channel was near elevation 236 feet. The top of the north bank was near 249 feet elevation, and the bank had moved 20 feet farther north since 1944

³⁴The deepest point in the streambed cross section, and generally the location of the river's maximum velocity.



Figure 9.--Overhead View of the U.S. Route 51 Bridge Site.

and centered on column bent 70. By October 1974, the construction of the southbound bridge was underway and the earthen embankments had been completed, constricting the Hatchie River flood plain to about 1,000 feet.

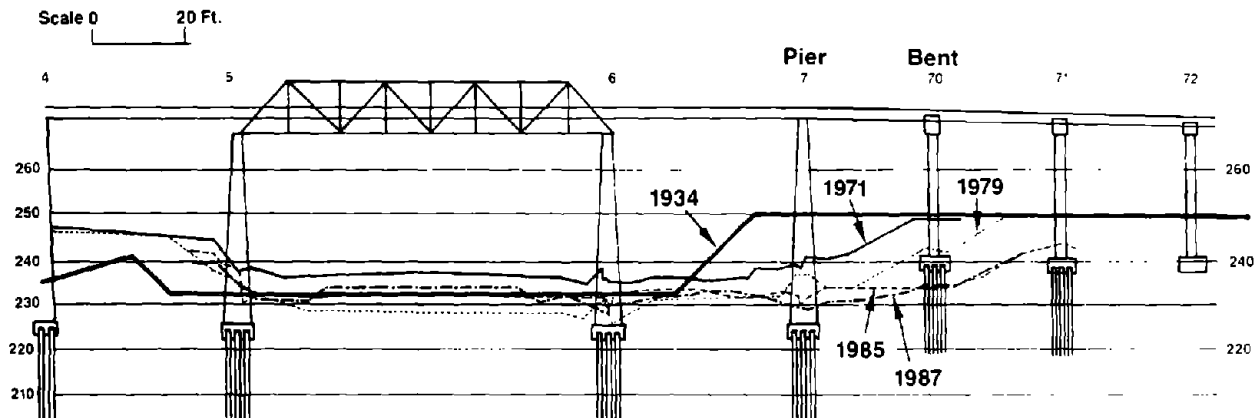
According to the USGS, between 1931 and 1975 the cross sectional area of the main channel at the bridge site decreased; however, the top width of the channel increased from 145 feet (1931) to 180 feet (1975), moving northward at an average rate of about 0.8 feet per year. Between March 7 and March 20, 1975, a "high-flow" period occurred at the site.³⁵ During this period the channel bed elevation at the bridge site dropped about 6 feet. The USGS study indicated that "Previous discharge measurements at the same section had not shown this type of dramatic bed-level lowering even during high discharge periods." During the March 1975 flood, the cross-sectional area of the main channel increased by over 600 square feet, but the channel top width did not change.

Between 1975 and 1981, following the construction of the southbound bridge, the top of the north bank moved 27 feet farther north, at a rate of about 4.5 feet per year. In 1979, the top of the north bank was about midway between column bents 70 and 71, and by 1983 the toe of the north bank had eroded underneath the bottom of the footing³⁶ of column bent 70. From 1981 to 1989 the main channel continued to move northward, although at a slower average rate of about 1.8 feet per year. In total, the main channel of the Hatchie River had migrated northward about 83.4 feet between 1934 and April 1, 1989. (See figure 10.)

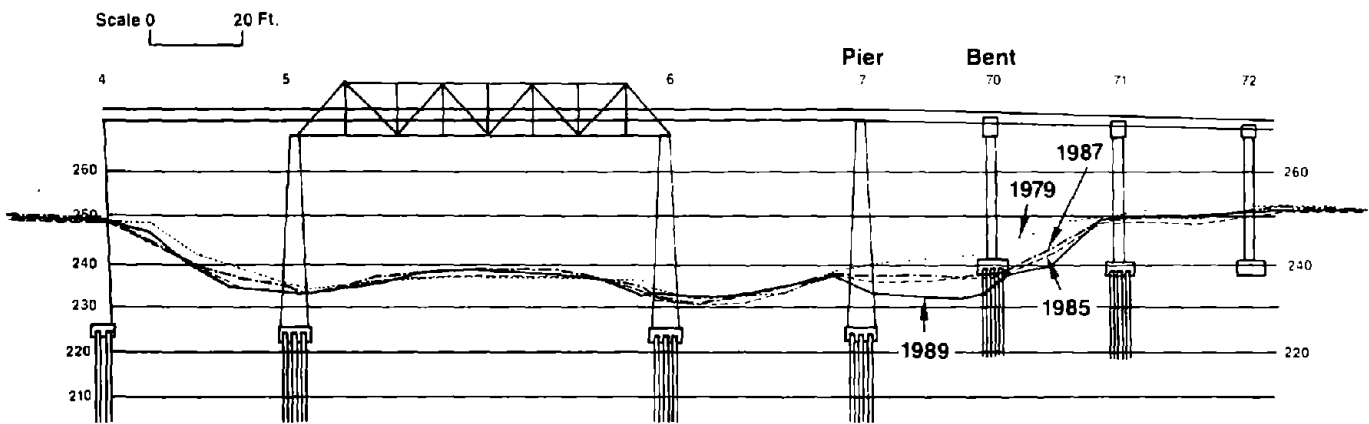
The USGS indicated that prior to 1975, the Hatchie River was following a natural, generally uninduced cycle of channel meandering, moving northward at an average rate of about 0.8 feet per year. The channel-bed lowering that occurred in March 1975 may have been solely due to high flow, "However, there was no serious bed lowering or widening in conjunction with a March 1973 high flow of 52,000 cfs" (about a 25 year flood event). The USGS stated that it was unlikely that the March 1975 moderate peak flood would cause the pronounced bed-level lowering, "if the hydraulic characteristics had not been significantly altered by the reduction in effective flow-width caused by the new embankments." A 1973 USGS study of "Man Induced Channel

³⁵During this time the gaging station for the Hatchie River at the U.S. 51 bridges was not in operation due to construction of the southbound bridge. A gaging station on the Hatchie River at Bolivar, Tennessee (about 101 river miles upstream) registered a March 7 flood of 7,950 cfs (about a 1-year flood event), and a March 20 flood of 35,800 cfs (about a 6-year flood event). The USGS indicated that a comparison of data from the Bolivar gage with the U.S. 51 gage showed a consistently similar high flow event ranking.

³⁶According to bridge design plans, the bottom of the column bent 70 footing was located at elevation 237.9.



MIGRATION BASED ON T.D.O.T. INFORMATION
 (DATA MEASURED AT THE NORTHBOUND BRIDGE)



MIGRATION BASED ON C.O.E. DATA FROM THE
SOUTHBOUND BRIDGE

Figure 10.--Channel cross sections from the Hatchie River at the U.S. 51 crossing.

Adjustments in Tennessee Streams"³⁷ states:

Stream channels tend to be among the most actively changing of all geomorphic forms. An alluvial river channel, for example, is continually changing its position and shape as a response to varying hydrologic conditions and to hydraulic forces acting on its bed and banks. These changes may be slow or rapid and may result from natural environmental conditions or from man's activities... According to the concept of channel equilibrium (Mackin, 1948), modifications made to a river channel will cause channel adjustments..."

The USGS indicated that as the reach of a channel changes or is altered, it will adjust its velocity, slope, roughness, geometry, and pattern of channel shifting until the channel morphology again comes into equilibrium. The USGS stated that the increased northward migration of the main channel between 1975 and 1981, (an average of about 4.5 feet per year), was the result of the river adjusting to accommodate the flood plain constriction caused by the embankments of the southbound bridge.

Further, the USGS concluded that the deceleration of the main channel widening after 1981 (an average of about 1.8 feet per year) indicates that the channel is still adjusting to an alteration in channel conditions, but may be slowly approaching a more stable configuration. The USGS also indicated that the "largest recent changes to channel shape appear to have occurred at the main channel north bank in the form of toe removal."

In its study, the USGS also considered the downstream north side flood plain clearing as a possible cause of the accelerated channel widening that occurred between 1975 and 1981. However, the USGS stated that the channel widening rates had begun to decrease when this flood plain was cleared and stated "this indicates that the flood plain clearing probably did not cause increased channel widening."

Hydrologic Information.--The USGS also conducted a hydraulic and geomorphic evaluation of the Hatchie River reach in the area of the U.S. 51 bridges from April 6, 1989 to April 10, 1989. The USGS performed an analyses of water velocities in the Hatchie River and the location of the thalweg at various locations along the main channel. The thalweg was located near the south bank of the channel 515 feet upstream from the midpoint of the northbound bridge. The thalweg moved northward as it approached the bridge; 190 feet upstream of the northbound bridge it was to the north of the center of the channel; 45 feet upstream the thalweg was near the north quarter point of the channel; and for a reach of about 205 feet from the upstream side of the northbound bridge to a point downstream from the southbound bridge the thalweg was near the north bank. The USGS concluded from these observations

³⁷ Ibid, 27, Factors Affecting Channel Stability, p.4.

that the flow was "probably undercutting the right [north] bank" in this 205-foot reach.

The USGS measured water velocities across the river at 20 percent depth, 80 percent depth and about 1-foot above the streambed. The velocities 515 feet upstream from the northbound bridge were uniform for the 20 and 80 percent measurements and the maximum velocity occurred at the 80 percent depth near the south bank. The USGS stated that the measurement, 1-foot above the streambed, was "variable." One hundred and ninety feet upstream of the northbound bridge, the 20 and 80 percent measurements were uniform, but the lower streambed measurement was variable, possibly due to a flow deflection caused by a hump in the streambed profile 150 feet from the south bank. At the upstream side of the northbound bridge, the flow velocities were variable and smaller at the north sides of the piers indicating that the flow was skewed northward. When the measurements were taken, the maximum velocity at the northbound bridge was not in the north bank thalweg. The USGS stated that the variability in the velocity profiles and the northward skew of the flow may indicate the possibility of a natural spiral flow pattern which is commonly associated with river bends.

Soil borings made in October 1974 for the construction of the southbound bridge indicated that the main channel was composed of deep sand and that the flood plains were generally composed of silt overlying deep sand. The streambed was measured at an elevation of about 235 feet and the silt/sand boundary near the north bank was at an elevation of 243 to 245 feet.

The USGS stated in its evaluation that cross-section geometry and velocity distributions "indicate that there is a high-flow meander pattern through the study reach. The bridges are located at or near the apparent meander inflection point." Further, the USGS concluded that because of the silt over sand soil characteristics of the north bank at the bridge and the northward skewed spiral flow of the river, the toe of the bank would be susceptible to undercutting of the sand strata, creating a condition of mass wasting, or sloughing of the upper silt strata. The USGS indicated that bank mass wasting is the most common type of bank failure that causes channel widening in meandering streams in west Tennessee.

Examination for Scour.-- Between April 7, and April 10 1989, CEI engineers conducted sounding and sub-bottom profiling of the Hatchie River streambed using a FHWA boat equipped with low frequency sonar, a recording type fathometer, and ground penetrating radar. Depth soundings were taken along lines parallel to the bridges; at both faces of the northbound and southbound bridges; on lines 50 feet upstream and downstream of the bridges; and around the piers and column bents in the main channel. The engineers used the low frequency sonar to determine if infilling of scour holes had occurred at the site, and to determine if there were detectable differences in the density of subsurface streambed material near the bridges. Sub-bottom data were collected along the same lines used for the soundings. Ground penetrating radar equipment was also employed to detect infilling, but suspended material in the water, coupled with water depth, precluded its effective use.

According to CEI engineers, after the collapse the streambed elevation measured 232 feet above sea level at both the upstream and downstream sides of the northbound bridge. Near column bent 71, the upstream bed elevation measured 236 feet, and the downstream bed elevation was 234 feet. At pier 7, the upstream bed elevation was 233 to 234 feet, and the downstream bed elevation was 238 to 240 feet. CEI indicated that the southern bank appeared to be just south of pier 4 and the north bank appeared to be just south of column bent 72. Fifty feet upstream from the northbound bridge the streambed elevation averaged about 236 feet.

Sub-bottom profiling indicated that in many areas adjacent to both the northbound and southbound bridge piers and column bents, there was a layer of less dense material, "probably infilling", on the channel bottom which ranged from 1 to 3 feet thick. Because of the debris in the area and the location of the collapsed spans, the engineers were not able to determine if there were any scour holes at column bents 70 and 71.

Bridge Inspection

Pre-collapse TDOT Office of Bridge Inspection.-- The Tennessee Department of Transportation operates under the direction of an appointed commissioner. Prior to the bridge collapse, the immediate subordinate to the commissioner was the State transportation engineer. Engineering activities within the TDOT were subdivided into the Bureau of Planning and Development (BPD), and the Bureau of Operations (BO). Each bureau was managed by an executive director who reported directly to the State transportation engineer.

The BPD was divided into four operating divisions, each division was managed by a division director who reported to one of two assistant bureau directors, who in turn reported to the bureau's executive director. The Structures Division within the BPD was further divided into the Hydraulics and Structure Office (HS), and the Bridge Inspection and Repair Office (I&R); each office was supervised by a Civil Engineer-Manager 2 (CEM2) who reported to the division director. The HS office was responsible for all TDOT hydraulic engineering activities including the preparation of preliminary hydraulic evaluations and designs, and the performance of scour studies. The I&R office was responsible for inspecting and evaluating the structural adequacy of the 18,591 existing bridges on public roads statewide, and developing plans and specifications for bridge repairs. The I&R office was subdivided into the Structures Inventory and Appraisal section (SI&A), and the Structural Steel Inspection and Repair section (SSI&R). Additionally, the I&R office contained four regional inspection offices with at least three inspection teams in each office.

According to the 1985 TDOT organizational manual, the SI&A section was responsible for (a) coordinating structural inventory data collection, (b) training and directing regional bridge inspection teams, (c) furnishing prints of all available drawings to those teams, (d) evaluating all bridges to determine load carrying ability, (e) reporting structural inventory and appraisal data to the FHWA, (f) initiating recommendations for posting or

closing structurally deficient bridges, (g) recommending priorities for structural rehabilitation, replacement and repairs, and (h) maintaining a computer inventory of all bridges on public roads. The SI&A section was further divided into the inventory group and the evaluation group.

The SSI&R section was responsible for (a) preparation of plans for existing structures needing repairs or maintenance, (b) conducting on-the-job training for inspection personnel, (c) designing and preparing structural drawings for repairs to existing structures accomplished by TDOT, and to a limited degree, local forces as well as contractors, and (d) providing limited direction to State and local maintenance forces engaged in repair activities.

The northbound U.S. 51 Bridge was located within the geographical area of responsibility of the Region 4 Inspection Office. This region was staffed with four 6-man inspection teams that reported to a regional inspection engineer who in turn reported to the I&R office CEM2. There were about 5,700 bridges in region 4. According to the FHWA Tennessee Division Office the engineers and inspectors within the SI&A office and the regional inspection offices met the National Bridge Inspection Standards (NBIS)³⁸ requirements for their respective positions.

Pre-collapse TDOT Bridge Inspection Policies.-- According to the I&R office CEM2, the regional inspection teams biennially inspect all State, County, and City bridges within Tennessee. During the Safety Board's public hearing, the region 4 inspection engineer indicated that prior to each bridge inspection, the regional inspection office prepared detailed inspection sheets based on the bridge design plans. The sheets were then used during the bridge inspections in lieu of the design plans. The inspection teams performed on-site inspections, rating each bridge element, and submitted detailed inspection reports, with comments, to the regional inspection engineer. The inspection engineer then compiled the field data submitted by the inspection teams, reviewed this data for accuracy, and rated the overall condition of the bridge. Both the individual element ratings and the overall bridge rating were defined as good, fair, poor, or critical. According to the region 4 inspection engineer, a good rating signifies that either no, or only minor, maintenance deficiencies existed; a fair rating signifies that no serious deficiencies existed; a poor rating signifies that serious deficiencies existed and repairs should be made as soon as practical; and a critical rating signifies that serious and potentially hazardous deficiencies existed and repairs or other remedial action should be taken as quickly as possible. During the Safety Board's public hearing, the inspection engineer indicated that an inspector would have to notice some settlement or leaning of a structure before it would be rated critical. The inspection engineer also formulated maintenance recommendations based on the

³⁸See appendix C for the complete NBIS as promulgated in 23 CFR Part 650, Subpart C.

information in the inspection reports, and transcribed the maintenance recommendations, ratings, and comments onto a computer summary. This computer summary and the detailed inspection report were then to have been forwarded to the inventory group within the SI&A office.

The inventory group organized each report, retrieved the previous inspection report, and submitted both reports to the evaluation group. According to the I&R Office CEM2, the evaluators then reviewed each page of the inspection report, compared the report with the previous inspection report, performed load rating calculations if necessary, and determined whether additional recommendations were needed. If the evaluators determined that a deficiency in the bridge was critical and required immediate attention, they advised their supervisors who would then discuss the deficiency with the CEM2. A telephone call would then be made by the I&R Office CEM2 to the Regional Director to advise him of needed load posting, closure, or urgent repairs to defer posting or closure. (See the Maintenance and Repair section for further information of TDOT maintenance procedures.) The evaluators could also initiate a bridge evaluation report (BER) for less critical repair items. The BER was sent to the appropriate Regional Director recommending action, and a written response from the region outlining the repairs performed was required to be submitted to the I&R office. Further, the regional inspection office forwarded the computer summary of the bridge rating and maintenance recommendations to the Regional Director or the appropriate local agency. There was a 6-month follow-up report required for the maintenance recommendations; however, this report only indicated which recommendations had been completed. There was no report procedure for those recommendations which had not been acted on, and there was no priority ranking for the maintenance recommendations.

Additionally, in 1986 the TDOT developed an underwater inspection program using divers. TDOT contracted engineer/divers to inspect the underwater members of bridges that were continuously in 10 feet or more of water. The I&R office CEM2 indicated that the 10-foot depth was an initial "cut", and that the criteria could be altered in future inspections. About April 1, 1990, TDOT adopted a new policy which requires divers to inspect bridges with more than 3.5 feet during low water. Further, the I&R office CEM2 indicated that TDOT has performed underwater inspections of bridges using divers based on recommendations from inspectors or evaluators. The I&R office CEM2 testified that the northbound U.S. 51 bridge was not included in the list of bridges that were to receive an underwater inspection using a diver because the Hatchie River maintained less than 10 feet of water in late summer and early fall.

Chronology of the Northbound U.S. 51 Bridge Inspections.--The northbound U.S. 51 bridge had been inspected by TDOT personnel 8 times since 1971. Beginning in 1975, the inspections occurred at 24 to 26 month intervals, and the last formal inspection prior to the collapse was completed in September 1987. None of the inspections included underwater diving. The Safety Board examined copies of the 1971, 1979, 1985, and 1987 TDT field

inspection reports, and FHWA structure inventory and appraisal summary reports for inspections conducted in 1975, 1977, and 1983.³⁹

The 1971 inspection report indicated that the bridge was structurally sound and in generally good condition. The senior engineer involved in the inspection wrote:

"While minor items of fault and deterioration were found, the major problem is due to improper expansion. Both ends of the bridge have expanded 8-10 inches past the abutments. This expansion has caused cracking in the backwalls over each abutment and leaning of the pile bents near each end of the bridge. There are fine cracks (not open) in nearly all other backwalls [span ends]."

The report also indicated that the steel bearing plates for the majority of the spans, including spans 77, 78, and 79, were corroded, and that some of the exterior girders had minor spalling⁴⁰ near the bearing areas. Further, the inspection was conducted while the river was at flood stage. The inspection crew measured 4 feet of abrasion on the surface of column bents 70 and 71, and the report indicated that the footings were not exposed. The report also indicated that the south bank was about 15 feet south of pier 5, and the north bank was about 15 feet north of pier 7.

The 1979 inspection report rated the overall condition of the bridge as fair. The inspection identified some minor spalling of the girder ends of spans 77 and 78, and corrosion of the steel expansion plates in both spans. The report indicated that the south bank of the main channel was 15 feet south of pier 5 and the north bank was 20 feet north of pier 7. Sketches from the report showed a 241.9-foot streambed elevation⁴¹ around the upstream column of column bent 70, and a 245.9-foot streambed elevation around the downstream column.⁴² Also, the report indicated that the streambed elevation at column bent 71 was about 252.5 feet. The report contained maintenance recommendations to "repair girder ends over bents as required and many minor items need repair."

³⁹See appendix D for further information of the FHWA Structure Inventory and Appraisal summaries.

⁴⁰Spalls are circular or oval depressions in concrete caused by a separation of segments of the surface concrete, revealing a fracture parallel with and slightly inclined to the surface.

⁴¹Elevations in the TDOT inspection reports were measured in relation to the tops of the column bent caps. Design plans indicated that the elevation of the top of the column bent 70 cap was 271.9 feet, and the elevation of the top of the column bent 71 cap was 271.47 feet.

⁴²According to the bridge design plans, the top of the column bent 70 footing was located at elevation 240.9.

The 1985 inspection report rated the overall condition of the bridge as poor. The summary of the inspection report indicated that most of the expansion plates throughout the bridge had corroded, and that both abutments had moved as much as 13 inches. A majority of the exterior span girders had spalled at the ends. The east exterior girder of span 77 had a 12 by 12 by 5-inch measured spall on the end resting on pier 7. The summary further stated that "the channel has cut into the embankment at [column] bent 70 and 71." The report indicated that from the top of bent cap 70 to the water level, a distance of 28 feet was measured. From the water level to the streambed a distance of 9 and 10 feet were measured at the west and east columns, respectively. Further, measurements around bent 71 indicated that from the bottom of the bent cap to the ground at the east column the distance was 21.2 feet. Along the west column of bent 71 the distance from the bottom of the bent cap to the water line was 23.5 feet and the water was six inches deep. The report also indicated that the channel scour could not be rated because the length of the columns for column bents 70 and 71 were unknown. TDOT indicated that this type of comment was used by the field inspectors to trigger a review in the regional inspection office. The report contained a variety of maintenance recommendations including patching of the exterior girders of span 77, and "Protect pier 5, 6, 7 and 70 from scour." No priority was assigned to these maintenance recommendations.

The last field inspection of the northbound bridge prior to the collapse was conducted in September 1987 and was performed by two 5-man TDOT crews that were both supervised by an inspection crew chief. The inspection report rated the overall condition of the bridge as poor "due to overall deterioration and alignment." Generally, the inspection report identified many of the deficiencies that had been noted in the previous inspection reports.

Additionally, the 1987 inspection report notes indicated that there was erosion of the north bank around column bent 70, and drift underwater at piers 6, 7, and column bent 70. Further, the report summary stated that "Channel has widening around bent 70 with scour below the footing. With pier 5 on edge of channel with pier 6, 7, being in channel. A large drift has accumulated around pier 6 & 7 and on column bent 70, and across channel adding to scour problem. Drift is mainly underwater. [sic]"

The 1987 inspection rated column bent 70 fair except for the item scour, which was a category added by the inspector, and was rated poor. The inspection report contained a sounding sketch and profile sketch of the streambed around column bent 70. (See figure 11.) These sketches indicated that the water level during the inspection was 30.5 feet from the bent cap or 1-foot above the footing.⁴³ The report further indicated that the depth of water at column bent 70 ranged from 6.6 feet to 8.5 feet. During the Safety Board's public hearing, the inspector who made these measurements indicated that he used a 25-foot fiberglass rod to probe around the footing, and believed that the footing was 5 feet deep. The inspector indicated that he

⁴³Based on the footing elevations in the bridge design plans, the water level during the 1987 inspection was about 241.9 feet elevation.

developed the 5-foot footing depth by feeling along the side of the footing with the rod. Based on this 5-foot deep footing measurement, the inspector's profile sketch indicated that the streambed was 1-foot below the bottom of the column bent 70 footing, with an average 7-foot water depth. Further, notes on the profile sketch indicated that "ground line is below bottom of footing. There is a large drift under the water - can not tell how large. 2-8" dia. tree. [sic]" The inspection report indicated fifteen feet north of column bent 70, the water depth was 2 feet and the bank was shown to the north of the 15-foot measurements.

The computer summary of the inspection contained a maintenance comment to repair scour under the footing of bent 70; however, there was no corresponding maintenance recommendation associated with this comment. There was a maintenance recommendation to "Clear drift". There were no BER's issued from the SI&A section as a result of this inspection. During the Safety Board's public hearing, the I&R office CEM2 stated that the "87' inspection adequately noted the scour activity occurring at that bridge. In the evaluation process the evaluator thoroughly reviewed that information and concluded that it was not significant enough to warrant an interim inspection." The I&R office CEM2 also indicated that in 1987, the pile exposure that was indicated on the inspection report would not have been considered critical. In 1988, the SI&A section recommended that the northbound bridge be considered for contract repair along with other bridges of the same priority (priority 2). The portions that were indicated for repair included the truss and concrete spalling of the superstructure girders.

During the week of February 28, 1989, the Region 4 inspection teams made a visual inspection of all State route bridges subject to high water conditions during the recent flooding. As part of this effort, the regional inspection personnel drove across the northbound U.S. 51 Bridge and looked over the sides of the bridge. The regional inspection engineer, indicated that the team "found no structures in Region 4 in immediate danger at the time of this inspection. A number of large drifts were noted but no structure settlement or misalignment was detected." Three bridges were noted that had settlement problems in a memo to CEM2. The regional inspection engineer testified at the Safety Board hearing that he could not recall any drifts or anything special that the team cited with respect to the northbound U.S. 51 Bridge.

Maintenance and Repair

Pre-collapse TDOT Office of Bridge Maintenance.-- Within the TDOT Bureau of Operations, routine bridge maintenance responsibilities are divided among 4 regional offices. According to the 1985 TDOT organizational manual, the functional objective of a regional office is to provide for the construction and maintenance of all interstate, federal-aid primary and State highways within the designated geographical boundaries of the region, and to provide for the administration of the State-Aid programs within the counties in the region. Some of the maintenance responsibilities of the regional offices are (a) to recommend and assist in the development of highway

maintenance, special projects and betterment programs, (b) to provide for the maintenance of all highway equipment in the region, including a region-wide bridge preventive maintenance program, and (c) to coordinate region-wide bridge repair with the regional bridge inspection office and structures division.

Each region is managed by an engineering director who reports directly to the BO director. Highway and bridge maintenance activities are coordinated within each region by a maintenance engineer. Reporting to the maintenance engineer is a regional maintenance supervisor who evaluates maintenance needs, and supervises two 6-person maintenance crews that perform major bridge maintenance within the region. The northbound U.S. 51 Bridge was located in region 4 which is subdivided into 5 District Offices. Minor bridge maintenance within the region is performed under the management of a district maintenance superintendent.

TDOT Bridge Maintenance Policies.--Regional engineering directors receive recommendations for closing, load posting, and bridge maintenance and repair from the I&R office of the BPD via a telephone call, a BER, or computer transmitted maintenance recommendation. Further, the computer transmitted maintenance recommendations are sent by the inspection office in each region to the regional engineering directors. During the Safety Board's public hearing, the region 4 engineering director indicated that he would review the telephone call and BER requests for bridge maintenance and repair and then pass the recommendations to the maintenance engineer.⁴⁴ The computer-transmitted maintenance recommendations would not normally be reviewed by the regional engineering director prior to being given to the maintenance engineer. All of these recommendations would be evaluated by the regional maintenance engineer and then given to the regional maintenance supervisor. The regional engineering director indicated that the telephone calls and the BERS would receive priority for maintenance, and that all would receive attention either by TDOT forces or contractors. Further, he indicated that the telephone calls would be acted on immediately; however, some of the BER's may not receive immediate attention. The maintenance supervisor indicated that he personally performed cursory field reviews of each telephone call recommendation and BER to evaluate their priority for maintenance. Computer transmitted maintenance recommendations were passed along to the district maintenance superintendents for minor repairs. Major repairs were performed under the direction of the maintenance supervisor, or by contract. The region 4 director testified that because of budget and manpower constraints, less than 50 percent of the annual computer transmitted recommendations were accomplished. During the 15 months prior to the collapse, region 4 received 58 BER's from the I&R office, and maintenance recommendations for 1,442 bridges from the region 4 Inspection Office. The northbound U.S. 51 bridge had 42 maintenance recommendations in the computer print out.

⁴⁴At the time of the collapse, the region 4 maintenance engineer was not a graduate engineer.

TDOT Maintenance of the Northbound U.S. 51 Bridge.--A review of the maintenance records for the northbound U.S. 51 Bridge revealed that most of the maintenance performed entailed drainage work, cutting and mowing of brush under and alongside the bridge, and asphalt patching. Maintenance personnel testified that they did not see drifts in the channel. There were no indications in the records or from testimony that drift had been cleared from the main channel, or that actions had been performed to protect column bent 70 from scour. The regional inspection engineer testified that the 1985 maintenance recommendations concerning scour were transmitted to the regional engineering director. However, the 1987 computer summary listed scour as a comment rather than a maintenance recommendation; therefore, the inspection engineer indicated that the recommendations concerning scour never reached the region engineering director.

The maintenance records also indicated that a district maintenance crew was cleaning debris on the southbound bridge deck on the day before the collapse. When interviewed, the maintenance crew members indicated that they traveled over the northbound bridge and had not noticed anything unusual about the northbound bridge on that day.

Post-collapse Revisions to TDOT Bridge Inspection and Maintenance Organization and Policies.-- During the Safety Board's public hearing in November 1989, TDOT indicated that in October 1989 the organizations that dealt with bridge inspection and maintenance within Tennessee had been modified and this resulted in procedural changes. The name of the I&R office has been changed to Bridge Inspection and Maintenance, and the office has been removed from the structures division and now reports directly to a deputy commissioner. Also, the regional inspection teams have been combined with the regional bridge maintenance crews, and are now supervised by a regional bridge engineer who reports to the regional engineering director. TDOT indicated that the flow of the inspection reports would remain the same but the regional bridge engineer would now have the opportunity to review the recommended maintenance and supervise maintenance activities between the regional bridge inspection teams and the regional bridge maintenance crews.

During the public hearing, the I&R office CEM2 indicated that inspection teams were now plotting channel profile measurements and these measurements were to be included in the inspection reports. He further indicated that as a result of the FHWA technical advisory on scour,⁴⁵ the regional bridge engineers and the SI&A evaluators would place more emphasis on scour notations and recommendations in inspection reports. Also, the SI&A evaluators may discuss individual inspection reports with the hydraulic section, and may further request a scour evaluation based on TDOT inspection reports. However, the I&R office CEM2 indicated in testimony that there was no written policy to assure that inspection reports received greater scrutiny when scour was indicated. He indicated that TDOT was now relying heavily on material in the technical advisory on scour to guide evaluations on assessing scour.

⁴⁵Technical Advisory, "Scour at Bridges," T 5140.20, Federal Highway Administration, Washington, D.C., September 16, 1988.

TDOT Scour Studies

During the Safety Board's public hearing, the engineering manager of the hydraulics study group within the HS section indicated that SI&A evaluators base their decision to forward a bridge inspection report to the HS section solely on the evaluator's assessment of the hydraulic or scour conditions at the bridge. The procedure to forward reports to the HS section for further review was in place when the northbound bridge was last inspected in 1987, and remains unchanged. The engineering manager further testified that the 1987 inspection report for the northbound U.S. 51 Bridge was never forwarded to the HS section for review. Inspection reports that are forwarded to the HS section undergo an initial review and then, if necessary, an in-house evaluation or a USGS field scour study is requested to determine the severity of the scour problems.

In September 1988, TDOT, in cooperation with the USGS, developed a screening program to identify scour critical bridges. The first phase of the program consisted of USGS field studies of State route bridges 50 feet or longer. These field studies began in January, 1989 and included a USGS evaluation of the scour potential and channel migration for each bridge. The northbound U.S. 51 Bridge had not received a USGS field study because the Hatchie River had remained at flood stage from the inception of the program until the collapse. The hydraulic study group engineering manager testified that from these field reports and evaluations TDOT was developing an inventory of all stream crossings Statewide with respect to potential scour at each bridge. Additionally, since the bridge collapse, TDOT is using the data and all underwater reports on file to develop a list of bridges with exposed footings or piles. Currently, TDOT is using the information gathered by the USGS to assist regional bridge engineers with repair details for existing bridges. However, the hydraulic study group engineering manager stated that "later, the information will also be used to do a complete scour critical analysis" for each bridge with hydraulic and geomorphic problems. During the public hearing this engineering manager stated that all of the USGS field studies had been completed in west Tennessee and that a "significant amount" of the studies had been completed in the remainder of the State. He also indicated that TDOT had recently incorporated selected local bridges into a second phase of the program.

Load Restrictions

TDOT Load Rating Policies.--In 1972, 1976, and 1981, TDOT performed load rating calculations for the northbound bridge. The calculations were made using a dead load, ⁴⁶ with an H-15 and H-20⁴⁷ live load, and with an

⁴⁶A static load due to the weight of the structure itself.

⁴⁷A H-15 AASHTO design vehicle weighs 30,000 pounds with 6,000 pounds distributed to the front axle and 24,000 pounds distributed to a single rear axle, separated by 14 feet. An H-20 vehicle has the same axle spacing but the loads are 33 percent heavier than an H-15 vehicle.

HS-15 and HS-20⁴⁸ live load.⁴⁹ These analyses all indicated that the weakest member of the bridge was a tension member of the pony truss, and that the bridge was capable of supporting an H-15 truck; however, the substructure elements of the bridge were not considered in these calculations. In February 1975, TDOT adopted a load posting policy that stated: "Bridges having an AASHTO H-15 vehicle inventory⁵⁰ rating or above are considered adequate to support the legal load permitted in Tennessee and are not posted." Following the collapse, the FHWA reviewed the 1972 TDOT load rating calculations and determined that they were accurate. The NBIS states that:

"Each structure required to be inspected under the standards shall be rated as to its safe load carrying capacity... If it is determined under this rating procedure that the maximum legal load under state law exceeds the load permitted under the operating rating, the bridge must be posted in conformity with the AASHTO Manual⁵¹ or in accordance with State law."

The AASHTO Manual further states that:

"A concrete bridge need not be posted for restricted loading when it has been carrying normal traffic for an appreciable length of time and shows no distress."

TDOT Overload Permits for the Northbound U.S. 51 Bridge.--The permits section within the TDOT Central Services Office issues all special permits for the movement of loads over highways that exceed the legal limits for width, length, height or weight. According to the I&R section CEM2 the permit office routinely issues permits for overweight vehicles (80,000 pounds or more), that are less than 150,000 pounds without conducting any analysis concerning the effect the overweight vehicle will have on highway or bridge structures. Vehicle permit applications that exceed 150,000 pounds are reviewed by the Structures Division in the BPD to determine the adverse effect of the load on the respective bridges. Following the review the Structures Division approves or denies the permit application.

⁴⁸An AASHTO design vehicle that weighs 72,000 pounds with 8,000 pounds distributed to the front axle, 32,000 pounds distributed to the first of two rear axles, separated by 14 feet, and 32,000 pounds distributed to the second rear axle, separated from the first rear axle by 14 to 30 feet. An HS-15 vehicle has the same axle spacing but loads are 75 percent of the HS-20 vehicle loads.

⁴⁹A dynamic load applied to the structure such as traffic load.

⁵⁰A load which can safely utilize a structure for an indefinite period of time.

⁵¹American Association of State Highway and Transportation Officials, Manual for Maintenance Inspection of Bridges, 1988 revised. AASHTO, Washington, D.C., 1988.

Between September 1, 1987 and March 1, 1989 (18 months), 1,368 overweight permits were issued by the TDOT Permit Office for U.S. Route 51 including the Hatchie River Bridges, an average of 76 per month. Permits are generally issued for 6-day periods. Between March 1, 1989 and April 1, 1989, there were 126 overweight permits issued including 36 permits that were valid on the day of the collapse. These permits ranged in weight from 82,000 to 150,000 pounds.⁵² However, these permits did not include weight per vehicle axle or axle spacing.

The Tennessee Highway Patrol Motor Vehicle Enforcement Division indicated that the only illegal overweight vehicle they stopped on the northbound U.S. 51 Bridge in March 1989 was a farm vehicle with 35,400 pounds on one axle.

Guidelines and Standard for Bridge Inspection.

National Bridge Inspection Standards.--On April 20, 1971, the FHWA issued the National Bridge Inspection Standards, which required that (1) all States have a bridge inspection organization, (2) inspectors meet minimum qualifications, (3) each structure be rated as to its safe load-carrying capacity, and (4) inspection records and bridge inventories be prepared and maintained in accordance with the standards. The standards further required that every bridge on a public road be inspected at regular intervals not to exceed 2 years. The depth and frequency of inspections depend on such factors as age, traffic characteristics, state of maintenance, and known deficiencies. The evaluation of these factors is entirely the responsibility of the individuals in charge of the inspection program, and the weight to be given these factors is not specified in the standards. Further, the standards establish qualification requirements for the individual in charge of the State bridge inspection organization and inspection team leaders. However, the NBIS has no qualification requirements for bridge inspection report evaluators, although reports generated by the inspection teams are frequently evaluated by qualified personnel supervising those teams.

The NBIS further requires that each State prepare and maintain an inventory of all bridges subject to the standards. The States are required to perform condition ratings of specific bridge elements as outlined in the FHWA Recording and Coding Guide for the Structure Inventory and Appraisal of the Nations Bridges. This information is then forwarded to the FHWA for inclusion in the National Bridge Inventory (NBI). From these condition ratings the FHWA determines a sufficiency rating for each bridge. The sufficiency rating is a numeric value which is indicative of bridge sufficiency to remain in service. The result is a percentage in which 100 percent represents a sufficient bridge and zero percent would represent an insufficient bridge.

⁵²See appendix E for a distribution of vehicle weights by the number of axles.

During the Safety Board's public hearing the Chief of the FHWA review and design branch indicated that the NBI data and sufficiency rating submitted by the States to the FHWA is used to administer the federal aid bridge program from a national level. The FHWA uses the information to estimate budget requirements and program bridge improvements, and to recommend program funding levels to Congress. The information is also used to administer the NBIS and to project future bridge needs. The Chief of the FHWA review and design branch testified that the information contained in the NBI was the minimum amount that the FHWA needed to administer the program at the national level and that the NBI did not contain maintenance information because maintenance activities are not part of the federal aid program. He further stated that "We just get generalized data that would be inadequate for administering or managing or operating a State [bridge] program, but it's perfectly adequate for national purposes." He also indicated that the sufficiency rating is used primarily to determine which bridges are eligible for federal aid highway program funds made available through the Highway Bridge Replacement and Rehabilitation Program. He testified that "as a strict priority setting or ranking tool, it's not a very good one," because the same data is gathered for all functional class highway bridges. Additionally, the TDOT I&R CEM2 testified that TDOT did not utilize the information developed for the NBI to schedule or prioritize bridge maintenance, or to determine bridge load ratings.

After the collapse of the New York Thruway Bridge near Amsterdam, New York, in 1987,⁵³ the FHWA revised the NBIS in December 1988 to place more emphasis on scour. The revisions included a requirement that the individual in charge of the organization unit that has been delegated the responsibilities for bridge inspection shall determine and designate on the individual inspection and inventory records and maintain a master list of:

"Those bridges with underwater members which cannot be visually evaluated during periods of low flow or examined by feel for condition, integrity and safe load capacity due to excessive water depth or turbidity. These members shall be described, the inspection frequency stated, and the inspection procedure specified."

Additionally, the FHWA added a "Scour Critical Bridges" condition rating to the NBI coding procedure⁵⁴ to identify bridges that are vulnerable to scour.

AASHTO and FHWA Bridge Inspection Guidelines and Standards-- Following the collapse of the New York Thruway Bridge, the FHWA issued a headquarters memorandum in 1987 to each State highway department notifying

⁵³For more information, see Highway Accident Report "Collapse of the New York Thruway (I-90) Bridge Over the Schoharie Creek Near Amsterdam, New York, April 5, 1987." (NTSB/HAR-88/02).

⁵⁴The NBI Coding Guide was issued in December 1988 and this change became effective in January 1990.

them to assess the vulnerability of their bridges to damage from floods. In September 1988, the FHWA issued a technical advisory (TA) entitled "Scour at Bridges," and an "Interim Procedures for Evaluating Scour at Bridges" to provide recommendations and guidance to the States on the development and implementation of a scour evaluation program. The TA recommended that States screen their existing bridges for potential scour problems, and then establish a program to prioritize bridges so that they can later be evaluated by an inter-disciplinary team of engineers. The TA indicates that the inter-disciplinary team should consist of structural, hydraulic, and geotechnical engineers. The TA further indicates that a "plan of action should be developed for each existing bridge determined to be scour critical... The plan should include a schedule for the timely design and construction of scour countermeasures determined to be needed for the protection of the bridge."

Further, the TA indicates that bridge inspectors should receive appropriate training and instruction in inspecting bridges for scour. The advisory also discusses the need to examine lateral stream shifting and to apply appropriate river training works and bank stabilization measures to control the lateral movement. The TA states that: "Perhaps the single most important aspect of inspecting the bridge for actual or potential scour is the taking and plotting of measurements of stream bottom elevations in relation to the bridge foundations." Finally, the TA provides guidance and procedures for estimating scour potential at bridge sites.

In November 1989, the FHWA issued manual FHWA-DP-80-1 "Underwater Inspection of Bridges" to augment the information contained in the Bridge Inspector's Training Manual.⁵⁵ The manual discusses most of the scour inspection information contained in the TA "Scour at Bridges." It also, provides guidelines for underwater bridge inspections, inspection techniques and equipment, and presents methods of repair for commonly found defects.

The 1983 (1988 revised) AASHTO Manual for Maintenance Inspection of Bridges discusses a variety of topics associated with scour inspections and bridge substructure inspections. At the time of the collapse, the Manual indicated that nonredundant bridges, and those with potential foundation and scour problems, may require interim and more intense inspections than normally required for ordinary bridges. The manual further indicated under "Inspection Procedures" that:

"Maintaining a channel profile record for the structure and revising it as significant changes occur provides an invaluable record of the tendency toward scour, channel shifting, degradation, or aggradation. A study of these characteristics can help predict when protection of pier and abutment footings may be required. Being able to

⁵⁵Federal Highway Administration, Bridge Inspector's Training Manual 70, FHWA, U.S. Department of Transportation, Washington, D.C. 1979.

anticipate problems and taking adequate protective steps will avoid or minimize the possibility of future serious difficulties."

The manual further indicated under "Inventory Reports" that:

"A sheet showing the channel profile at the upstream side of a bridge over a waterway should be a part of the original report. The sketch should show the foundation of the structure and where available description of material upon which footings are founded, the elevation of the pile tips, and/or the footings of piers and abutments. This information is valuable for reference in anticipating possible scour problems through yearly observations and is especially useful to detect serious conditions during periods of heavy flow."

In 1987, revisions to the Manual indicated that any exposed piling must be inspected, and that exposed timber piles must be checked for decay.

FHWA Oversight of the TDOT Inspection and Maintenance Program

The FHWA reviews State bridge inspection programs to determine if a State is meeting load rating and inspection frequency requirements and has qualified inspectors; the FHWA also determines if the programs comply with the bridge inspection and inventory requirements. The reviews are conducted on three levels: (a) the FHWA division office conducts an annual review of the State's bridge inspection program, discusses with State officials the State's compliance with the minimum requirements of the NBIS, and reviews the inspection reports and load ratings of a sampling of bridges within the State; (b) the FHWA regional office conducts additional reviews to determine if the division annual review is reasonable and sound; and (c) the FHWA headquarters office in Washington, D.C., reviews regional programs and provides overall administration of the NBIS.

Since 1972, the Tennessee Division Office of the FHWA has annually reviewed TDOT's bridge inspection program. Since 1976, these reviews have included FHWA inspections of about 50 to 80 State and municipally owned bridges for comparison with TDOT inspection reports, and a review of bridge maintenance in response to TDOT inspection report recommendations. Overall, the most recent annual reviews highlighted the State's progress in load-posting State bridges and the State's ability to have local governments comply with NBIS for load rating and posting their bridges. According to the FHWA Division office, by 1987, most of the State bridges within Tennessee were properly load posted. However, many of the locally owned bridges were not in compliance with load posting requirements. As a result the FHWA in cooperation with TDOT instituted a program in which local governments were notified that Federal highway project funds would be withheld until those bridges that were not in compliance were properly load posted. During the Safety Board's public hearing, the FHWA Tennessee Division Chief testified that "at the county and city level, the situation had improved since our actions to defer Federal Aid projects."

The last FHWA regional review of the TDOT bridge program prior to the collapse was conducted on March 23-27, 1987. The review indicated that TDOT was improving the load posting compliance of local bridges. The review further indicated that the State had developed a list of about 170⁵⁶ structures that were continuously in 10 feet of water and were targeted for underwater diver inspections.

The review also indicated that the State did not have a list of non-redundant structures or structures that have fracture critical details, and FHWA recommended that the State attempt to increase the number of interim inspections between the 2-year cycle on selected bridges. Also, the review indicated that the initial criteria used by TDOT to prioritize bridge replacement and rehabilitation projects was the list of structures with an inventory load rating less than 15 tons. Finally, the review indicated that TDOT needed to obtain more reach-all type equipment to allow inspectors access to elevated bridge structures. Currently, all four regions have new reach-all equipment and three snooper trucks were recently rehabilitated.

FHWA conducted a division review of TDOT in 1988 and another regional review of TDOT in April 1989. In 1989 FHWA indicated that a scour screening process, in cooperation with the USGS, was in progress. In summary, FHWA indicated that TDOT was in substantial conformance with the NBIS requirements.

A May 1988, FHWA memorandum from the Associate Administrator for Engineering and Program Development to the Regional Administrators stressed the need to assure that critically needed maintenance activities were being performed by the States in response to recommendations from bridge inspection reports. The memorandum stated that "it is essential that each State have a system which assures that necessary work is accomplished. Equally important is the need for each division office to establish an on-going process to monitor the State's accomplishments relating to critically needed bridge maintenance..." The FHWA Tennessee Division Director testified that he believed that his office was already performing follow-up reviews of maintenance recommendations as part of the division annual inspection review process. However, as a result of this memorandum, the FHWA Division office asked TDOT for a list of critical bridges so that the FHWA could provide greater attention to critically needed maintenance during the annual reviews.

Additionally, the FHWA is currently stressing the need for maintenance follow-up action based on bridge inspection report recommendations in a series of "Bridge Management Tri-Regional Workshops." Similarly, TDOT stressed this area in a 1988 meeting with the Regional Directors.

⁵⁶The final number of bridges was 164 as indicated in the FHWA Division Annual Maintenance Report, November 9, 1987.

Tests and Research

Scour Analysis.--Following the collapse, the FHWA Turner Fairbanks Highway Research Center Hydraulic Laboratory conducted a hydraulic model study of column bent 70 of the northbound bridge. Three different model configurations of column bent 70 were evaluated: (1) the footings placed above the streambed to simulate approximately 5.9 feet of exposed pile;⁵⁷ (2) the first configuration was repeated with debris added around the upstream side of the exposed piles supporting the east footing; and (3) a bench mark model with the square columns placed into the streambed with no exposed footing or piles. The purpose of the study was to provide insight on the geometry and potential depth of local scour that could have occurred around column bent 70 before its collapse. The tests were conducted in a 6-foot-wide, 70-foot-long, 2-foot-deep, tilting flume that was equipped with a depressed section near the center to accommodate a sand bed for scour experiments. The debris used in the second model consisted of a bundle of saturated sticks, slightly wider than the footing, tied to the upstream piles near the streambed.

The study revealed that in the first model configuration, the measured "in flume" depth of scour around column bent 70 model was 3.3 feet located at the center exposed pile of the upstream footing. (See figure 12.) Scour was about 40 percent less at the downstream footing. The second model configuration revealed that the debris "did not appreciably increase the scour depth." However, FHWA researchers indicated that the scour hole could have been greater if the debris used in the model had been more dense. (See figure 13.) The third model configuration study indicated that scour around the embedded footing would have been more severe, measuring 4.3 feet. All 3 models experienced aggradation of streambed material between the footings.

Foundation Analysis.--Following the collapse, the FHWA Bridge Division conducted a foundation analysis of column bent 70 to determine the most likely failure mode of the substructure friction piles. The FHWA examined the axial pile-soil capacity, lateral pile-soil capacity, and pile buckling of the column bent 70 piles assuming several different streambed elevations caused by local scour. In the analysis, the FHWA assumed that the piles were 20 feet long, had a 12-inch diameter butt end and an 8 or 10-inch diameter tip, that the bottom elevation of the column bent footings was 238 feet, and that the streambed elevation without local scour was 231 feet. Further, the FHWA examined the column bent under two different vertical loading scenarios (an H-15 truck which along with the bridge dead load applied 90.5 tons on each footing, and an HS-20 truck which applied 112.8 tons on each footing), and under several local scour and drift conditions.

The FHWA concluded that the most likely failure mode was "a loss of vertical pile capacity caused by the removal of supporting soil material." Further, the FHWA determined that a pile buckling failure would only have

⁵⁷ Based on the bridge design plans indicating a footing bottom elevation of 237.9 feet, and assuming the lowest measured streambed elevation of 232 feet.

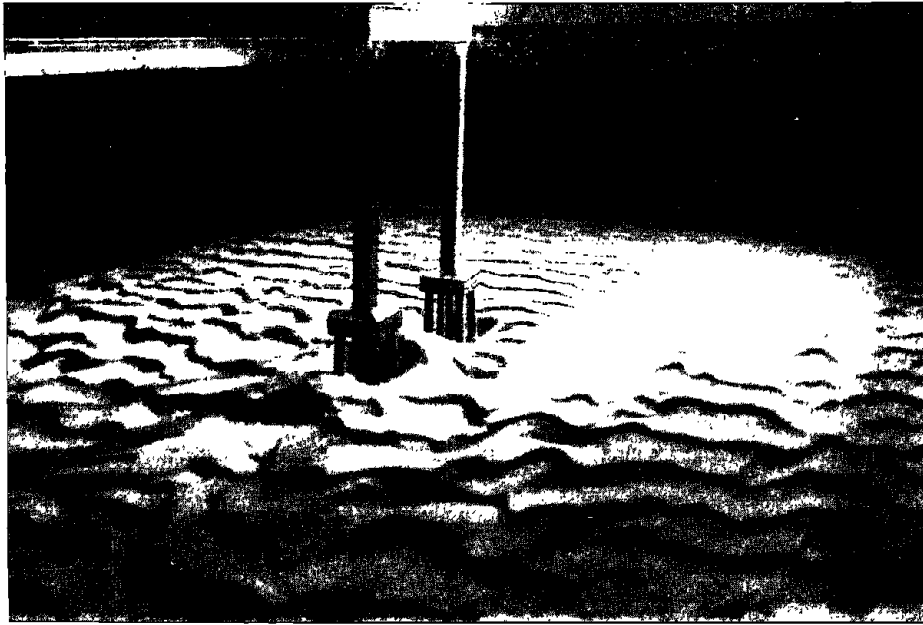


Figure 12.-- FHWA Flume Model Study (1).

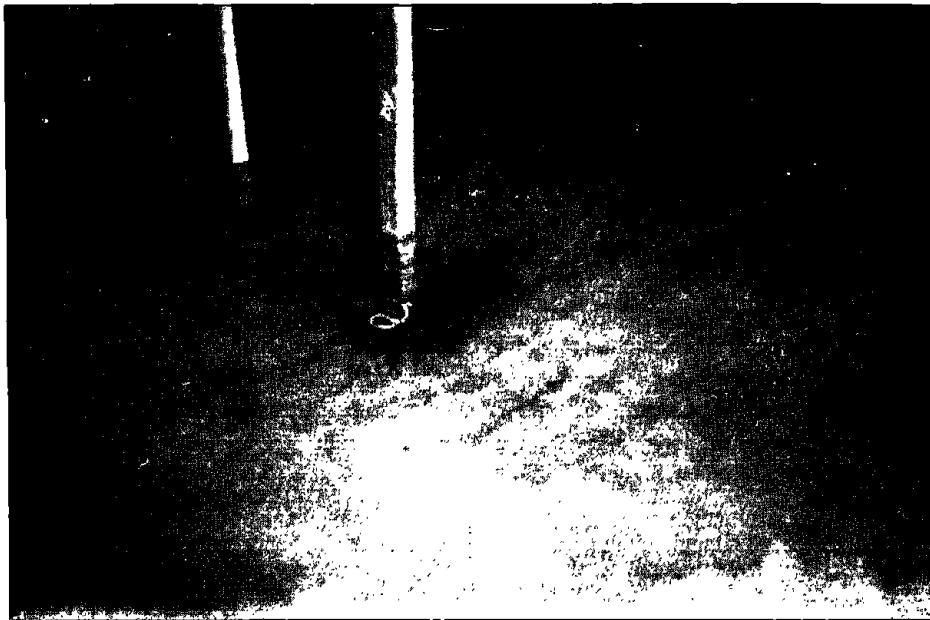


Figure 13.--FHWA Flume Model Study (2).

occurred initially if there had been a 25 percent reduction in the diameters of the timber piles, or if the piles had been almost entirely exposed. Additionally, the FHWA concluded that a failure of the pile-soil system under lateral loads was not a likely failure mode, even under maximum scour and drift conditions. However, the report stated that "based on several unknowns, i.e. installed pile length and condition of pile material, the exact cause of failure can not be stated."

Timber Pile Testing.--During the August, 1989 underwater examination of the bridge wreckage, CEI extracted 4 pieces (2 large samples and 2 small samples) of the timber piles from the submerged wreckage. These samples were then sent to the U.S. Department of Agriculture, Forest Products Laboratory (FPL) for examination. FPL determined that the two large samples exhibited bacterial and soft rot⁵⁸ surface decomposition to a depth of about 0.25 inch. A microscopic examination of the samples revealed that bacterial attack appeared to be predominant, and that the interior wood appeared sound. FPL indicated that the two smaller samples were severely decayed throughout, but did not appear to be part of the piles.

Other Information

Current Methods for Evaluating and Measuring Bridge Scour.--During the Safety Board's public hearing, the Chief of the FHWA Hydraulics and Geotechnical Branch of the Bridge Division indicated that "it's almost impossible to measure scour when you're doing a bridge inspection. Scour takes place at the peak of a flood event and then as the flood event recedes, the scour hole fills in. So, when the bridge inspection unit is there, typically they're measuring the nominal bed without scour." Currently, the FHWA is promoting the use of low frequency sonar and ground penetrating radar to detect infilling of scour holes. This equipment can determine the cross section soil density characteristics of streambed subsurfaces, and therefore detect scour holes that have been filled in. The FHWA is further providing demonstrations to each State concerning the use of this equipment along with other additional information concerning underwater bridge inspection equipment and methods. Additionally, static scour monitors are being developed to identify historical changes in the streambed due to scour. These monitors include instrumentation that is attached to a submerged bridge pier and measures the streambed over time.

The FHWA has recently established a "high priority" national research program entitled "Critical Substructure Bridge Elements." The FHWA indicated that the goals of the program were to develop better instrumentation for bridge inspectors in all facets of substructure bridge inspection, and to refine the methods that bridge designers use to estimate scour. The research program also involves revisions to the Bridge Inspectors Training Manual 70, and training for State bridge inspectors on identifying hydraulic and scour problems with bridges.

⁵⁸ Soft rot is caused by fungi related to mold and is prevalent in wet environments. The outer surface of the affected timber is degraded and the layers appear soft.

FHWA Bridge Management Program.--In the early 1980's, the FHWA determined that nationally, there was an imbalance between current and predicted bridge needs, and the repair or rehabilitation resources available to meet those needs. The FHWA indicated that: "Of the Nation's 576,000 bridges, 40 percent are either structurally deficient or functionally obsolete. To rehabilitate or replace these deficient bridges would cost approximately \$50 billion, a figure that had remained nearly constant for the past several years, despite a growing bridge improvement program with annual expenditures of about \$5 billion (including \$3 billion in Federal Aid) for replacing/rehabilitating about 10,000 bridges a year."⁵⁹

In cooperation with the States, the FHWA has researched methodologies to better manage available resources with future bridge needs. The FHWA concluded that while bridge owners generally have adequate management systems in operation to determine individual bridges in need of rehabilitation, replacement, or maintenance, a comprehensive bridge management system should be developed that would manage the entire bridge population at the network level rather than at an individual project level. Therefore, in 1986, The FHWA organized a demonstration project on bridge management systems.

According to the FHWA Bridge Management Systems Project Manual, the primary objective of a bridge management system is to assist the bridge program manager in using available resources in the most efficient and cost-effective manner to address current and future bridge needs. Further, a long term objective of a bridge management system is to eliminate the current backlog of bridge needs and to provide resources for bridge improvements each year that match the needs that accrue each year. The FHWA indicated that it is unlikely that States will be able to eliminate their backlog in the foreseeable future; however, the prospects for significantly reducing backlog can be enhanced with a comprehensive bridge management system.

During the Safety Board's public hearing, the Chief of the FHWA Review and Design Branch of the Bridge Division testified that the most important element of a bridge management system is for the State to develop overall goals, and then to establish minimum tolerable levels of service for bridges. Once this minimum tolerable level has been established, the State's can then establish rehabilitation priorities based on State goals and user needs. The FHWA Review and Design Branch Chief further testified that concerning bridge safety-- "the way it's handled at this point in time is to go ahead through your priority ranking and whatever formula is developed. Consider all those projects in your bridge management system, but you have a default element and that is a flag. Any time that a safety item pops up, it's automatically considered in your program."

⁵⁹ U.S. Department of Transportation, Federal Highway Administration, "Bridge Management Systems" FHWA-DP-71-01R, FHWA, Washington, D.C. October, 1989.

The FHWA is currently conducting bridge management presentations in each state to discuss and present comprehensive bridge management concepts. Further, as a second phase of the demonstration project, the FHWA, in cooperation with the California Department of Transportation is developing a generic bridge management program that can be used by the States as a guide.

ANALYSIS

General

The performance of the passenger car drivers and truck driver that fell into the river following the collapse did not influence the outcome of this accident. The collapse occurred at night on a rural bridge that had no artificial lighting, and in an area of the bridge which included a slight upgrade for approaching vehicles. Therefore, it is unlikely that these drivers were able to see the collapsed area of the bridge in sufficient time to stop their vehicles prior to falling into the river.

Seven of the 8 victims apparently died as a direct result of injuries they received when span 79 fell on top of their vehicles. The eighth victim was not crushed by falling bridge debris; however, the station wagon that he was driving sustained impact damage that penetrated into the passenger compartment. The post mortem examination of this victim revealed that he had received multiple fractures. This suggests that the driver may have been incapacitated during the accident and, therefore, probably drowned soon after his vehicle became submerged. As a result, the Safety Board concludes that the post-collapse emergency response could not have reduced the severity of this accident.

Failure Modes

Following the bridge collapse, four of the five accident vehicles were discovered underneath span 79. This indicates that the collapse of span 79 was a secondary event in the accident sequence. Further, because the northbound bridge spans were simply-supported, span 79 could not have remained in place without the support of column bent 71. Apparently, the collapse of column bent 71 was also a secondary event in the accident sequence. The vehicles that were located underneath span 79 sustained downward crush damage from the falling span, but also exhibited rearward deformation. A post collapse examination of the column bent 71 wreckage revealed that the south face of the bent cap had been scraped, and that paint marks were present at various locations along the bent cap. These paint marks corresponded to the colors of the passenger cars involved in the accident. Further, red paint marks, which corresponded to the color of the tractor involved in the accident, were discovered along the south face of the bent cap near the west column. Therefore, the Safety Board concludes that column bent 71 and span 79 were still standing following the collapse of column bent 70 and spans 77 and 78, and were struck by some or all of the accident vehicles before they collapsed.

Based on the bridge wreckage and vehicle damage, the Safety Board calculated that all of the passenger cars were traveling about 55 to 60 miles per hour as they fell off the bridge. An examination of the tire marks located on span 76 revealed that the dual marks were made by the left rear tires of the tractor's semitrailer. The trajectory of these marks extended from the south end of span 76 northward towards the standing position of the west column of column bent 71. Based on the tire marks and the bridge wreckage the Safety Board calculated that the tractor-semi-trailer was traveling about 38 mph when it fell off the end of span 76. Also, an examination of the column bent 71 wreckage revealed that the west column was fractured and that the bent cap had been pushed northward, rotating clockwise around the east column. Based on this information, the Safety Board concludes that column bent 71 may have been pushed slightly northward by span 78 as it fell. The west column of column bent 71 was then fractured, and the entire column bent and span 79 subsequently collapsed, as a result of the successive impacts from the passenger cars, and then finally the tractor-semi-trailer.

The post-collapse inspection of the Hatchie River streambed, and a review of historical channel profile data revealed that at the time of the collapse, the main river channel had migrated northward beyond column bent 70. As a result, the column bent footing and substructure friction piles, which were designed to be embedded beneath the flood plain, were exposed to water. Further, the collapse occurred during flood conditions when the potential for local scour, and lateral loading from higher stream flow velocities and debris were increased. Additionally, an examination of the bridge wreckage revealed that both columns of column bent 70 were fractured near the footings, and that the east column was also fractured at mid-length. This evidence suggested that the bridge collapsed as a result of a substructure failure of column bent 70. However, a review of the bridge inspection reports for the northbound U.S. 51 bridge revealed that the exterior girders of spans 77 and 78 were spalled at the bearing areas. Accordingly, the Safety Board evaluated the possibility of a failure of the bridge superstructure because of pre-existing deficiencies in the bridge girders, and the possibility of a failure of the bridge substructure because of the exposure of the piles supporting column bent 70, fractures in the column bent 70 concrete substructure members, excessive lateral loads due to water and debris, or pile deterioration.

Mode 1: Failure of the Superstructure.--A post-collapse examination of the wreckage of span 77 and 78 indicated that the spans appeared to have remained intact following the collapse. Additionally, a review of the TDOT inspection information concerning these spans did not uncover any serious pre-existing cracks in either the superstructure girders or diaphragms. However, the inspection reports did note spalling of the exterior girders of both spans. The northbound U.S. 51 bridge spans were designed to be internally redundant, transferring loads between the girders and diaphragms, and then transmitting those loads to the substructure elements. This internal redundancy would tend to lessen the effects of the exterior girder deterioration noted in the bridge inspection reports. Loads normally transmitted to the substructure through the exterior girders would have been transferred to the interior girders without a significant effect on the

bridge's load capacity. Additionally, the CEI divers who examined the submerged wreckage indicated that they found only minor broken concrete on the girder ends, and no significant distress in the girders. The Safety Board, therefore, concludes that the deterioration of the exterior superstructure girders of spans 77, 78, and 79 did not contribute to the bridge collapse.

Mode 2: Failure of the Substructure.--Following the collapse, the column bent 70 components remained submerged underneath the bridge superstructure components. As a result of the distribution of the submerged bridge wreckage, CEI divers were unable to fully examine the majority of the column bent 70 cap, or upper segments of the columns. Therefore, the Safety Board could not determine if fractures existed in these members. However, the position of the bridge wreckage indicated that the columns and bent cap fell together. If a fracture in the columns or bent cap had caused the collapse, it is likely that the column bent would have experienced some torsional movement, and therefore, would not have fallen uniformly. During an examination of the submerged wreckage, CEI divers also discovered a fracture in the middle of the east column; however, this fracture was located directly beneath the convergence of the submerged spans and was likely the result of the spans falling onto the column rather than from a preexisting deficiency.

Further, an examination of the bridge wreckage revealed that both footings had separated from the columns. However, it is unlikely that these fractures occurred prior to the collapse sequence. Although the majority of column bent 70 fell northward, both footings were located south of their original positions following the collapse. This southward displacement of the footings was probably the result of sudden eccentric loads placed on the top of the column bent by the falling spans. These loads may have forced the northward falling column bent downward, in turn creating a rotational effect on the column bent, forcing the footings to completely break away from the piles and move southward. Further, if these fractures of the footings had been the origin of the collapse, it is likely that the footings would have remained in place while the column bent fell. Also, CEI divers indicated that both the footings and bottom of the fractured columns had broken rebar extending as much as 6 inches from the fractured areas. This suggests that the fracture was the result of a tensile or bonding failure, and not a sudden shear failure, thus supporting the premise that the footings were still attached to the columns as the collapse sequence began. Therefore, the Safety Board concludes that it is unlikely that a fracture of the concrete members of column bent 70 initiated the collapse sequence.

During the recent investigation of the collapse of the S.R. 675 Bridge at Pocomoke City, Maryland,⁶⁰ the Safety Board determined that the bridge's 67-year-old untreated timber piles buckled as the result of a 35 percent reduction in their cross-sectional area. Thus the Safety Board sought to

⁶⁰For more information, see Highway Accident Report--"Collapse of the S.R. 675 Bridge Spans over the Pocomoke River near Pocomoke City, Maryland, August 17, 1988 (NTSB/HAR-89-04).

determine if a similar reduction or deterioration of the 53-year-old untreated timber piles of the northbound U.S. Route 51 Bridge also occurred. During the CEI examination of the bridge wreckage, four samples of the timber piles were extracted and forwarded to FPL for testing. The two larger samples had only 0.25 inches of surface deterioration, (a 5 percent reduction in cross-sectional area for an 11-inch diameter pile), primarily due to bacterial attack. This surface deterioration would not have significantly reduced the pile's load carrying capacity. The remaining two timber samples were severely decayed; however, FPL indicated that these samples did not appear to be from the piles. Further, the FHWA substructure analysis indicated that if there was no significant reduction in the cross-sectional area of the piles, an almost complete vertical exposure of the piles would have been necessary before they could have failed due to buckling. Even then, the piles would most likely have embedded prior to failing due to buckling. The FHWA foundation analysis also indicated that a pile buckling failure was possible if the piles had been reduced in diameter by 25 percent, (a 44 percent reduction in cross-sectional area), and if the piles had experienced more than 4 feet of local scour. According to the bridge inspection reports, the northbound U.S. 51 Bridge piles had been exposed to water less than ten years. When compared with the piles from the S.R. 675 Bridge, (35 percent cross-section reduction over 67 years), it does not appear likely that the U.S. 51 Bridge piles would have suffered this 44 percent loss in cross-sectional area due to water abrasion or degradation from bacterial attack after only 10 years. Therefore, the Safety Board concludes it is unlikely that the piles buckled as a result of a reduction in the pile cross-sections.

The cross sectional measurements of the Hatchie River streambed following the collapse indicated that the column bent 70 piles could have been exposed as much as 5.9 feet because of channel migration. Additionally, the FHWA scour analysis indicated that 3 to 4 feet of local scour could have occurred around the exposed column bent 70 piles. Further, drift accumulation around column bent 70 could have added to the depth of local scour. As a result, the timber piles supporting column bent 70 could have been exposed as much as 10 feet. The bridge design plans indicated that the piles were 20 feet long and that they were embedded 1-foot in the footings. Therefore, at the time of the collapse, it is likely that the piles supporting column bent 70 could have been buried only about 9 feet in the streambed. The FHWA foundation analysis indicated that the most likely failure mode was a loss of vertical pile capacity from the removal of supporting soil material around the piles. The analysis further indicated that the piles would embed if they were exposed 11 feet or more. However, this analysis assumed that the piles were 12 inches in diameter at the butt end. During the examination of the bridge wreckage, CEI divers determined that one of the column bent 70 piles measured 11 inches near the butt end. As a result, smaller diameter piles would require less exposure to embed. Therefore, based on this information, the Safety Board concludes that the most likely initial failure of column bent 70 was the embedment of the supporting timber piles, perhaps in combination with pile buckling, because of their exposure from a combination of channel migration and local scour.

Collapse Sequence of the Bridge

Based on the physical evidence, witness statements, bridge inspection reports, and research data, the Safety Board finds that the following sequence of events occurred, resulting in the collapse of the northbound U.S. 51 Bridge spans. Following the construction of the northbound bridge, the Hatchie River conformed to a pattern of natural channel migration moving northward at a average rate of 0.8 feet per year until 1974. In 1974, the constriction of the Hatchie River flood plain caused by the construction of the southbound bridge embankments reduced the available area (4,201 feet to 1,000 feet) through which flood waters passed downstream at the bridge site. In response to this flood plain constriction, the Hatchie River underwent a series of changes in an attempt to reach a hydrologic balance with the reduced flood plain opening. One of those changes was an increase in the northward migration of the main channel. By 1979, the north bank of the main channel was located about 20 feet north of pier 7 (when the bridge was constructed the north bank was located south of pier 7). The main channel continued to move northward at an accelerated rate until 1981. At that time, the channel began to reach a balance with the flood plain constriction and between 1981 and 1989 the rate of channel migration slowed. By 1985, the north bank of the main channel had moved north of column bent 70, and the streambed at the column bent was located about 4 feet beneath the bottom of the footing. By 1989, the streambed was 5.9 feet or more below the bottom of the footing. Additionally, the duration and severity of the 1988/89 flood season probably caused from 3 to 4 feet of local scour at column bent 70.

As a result of the combined effects of channel migration and local scour, the friction piles supporting column bent 70 became exposed to water as much as 10 feet and these piles were no longer capable of supporting the bridge loads. Therefore, about 7:15 p.m. on April 1, 1989, as vehicles passed over spans 77 and 78, the piles supporting column bent 70 began to embed, and the column bent began to lean northward. As a result, the 78-ton spans began to shift placing additional vertical and lateral forces on column bent 70 as they slid away from pier 7 and column bent 71. About 8:00 p.m., as additional vehicles passed over the spans, the piles continued to embed or buckle, creating the 2 to 3-foot depression in the bridge deck described by witnesses. Shortly afterward, the column bent fell northward and spans 77 and 78 fell into the river.

Following the collapse of column bent 70 and spans 77 and 78, several northbound passenger cars drove off of span 76, at 55 to 60 mph, and struck column bent 71. Immediately afterward a tractor-semitrailer drove off of span 76 at a speed of about 38 mph and collided with the west column of column bent 71. The left front of the tractor struck the column and the tractor rotated counterclockwise and collided with the bent cap. During this collision the trailer also struck the column, separated from the tractor, and fell into the river. This collision fractured the west column and forced the bent cap northeastward. As column bent 71 fell, span 79 also fell on top of the tractor and the passenger cars located under the span. Additionally, span 79 pushed column bent 72 northward about 2 to 3 degrees as it fell.

Adequacy of the Design and Construction of the Northbound Bridge

The northbound U.S. 51 Bridge appears to have been constructed to the AASHO and TDHPW standards that existed in 1931. The 1931 TDHPW specifications required that bridge piers be built parallel to the stream. The TDHPW straightened the channel to accomplish this, and further constructed the first northern flood plain support (pier 7) as if it were in the channel. Also, the AASHO specifications required that this bridge be designed to accommodate an equivalent H-15 truck. According to the design plans, the pony truss was designed for two 15-ton trucks placed abreast.

Neither the TDHPW or the AASHO specifications discussed simple or redundant bridge design. The northbound U.S. 51 bridge spans were designed with some redundancy within the spans; loads could be transferred between the girders and diaphragms, before being transmitted to the substructure elements. However, the remainder of the bridge was constructed to be simply-supported and could not transfer loads from one span to the next. Therefore, as the piles supporting column bent 70 began to embed or buckle, the load of spans 77 and 78 could not be distributed to other bridge support elements. This permitted the collapse to occur over a relatively short one hour period. The bridge may even have collapsed more quickly had it not been for the longitudinal movement of the entire bridge superstructure that was noted in the bridge inspection reports. This movement, the result of thermal expansion, forced the spans closer together. As a result of the spans closer proximity to each other, a temporary binding between spans may have developed as the bridge began to collapse. The spans may have been able to briefly support each other, in turn delaying the collapse. During the recent investigation of the S.R. 675 Pocomoke City Bridge collapse, the Safety Board determined that as a result of the redundant design of that bridge, the actual collapse extended over a period of several days and provided warnings of the degraded condition of the bridge. Therefore, the Safety Board concludes that the simply-supported spans of the northbound U.S. 51 Bridge allowed the collapse to occur with little warning over a short period of time. This accident further highlights how just one member of a simply supported bridge can fail and cause a sudden catastrophic collapse, as was noted in the Mianus, Chickasawbogue, and New York Thruway bridge collapses.⁶¹

During the examination of the submerged bridge wreckage, divers indicated that the column bent 70 footings appeared to be 3 feet deep and rectangular. The design plans indicated that these footings should have been tapered to 2 feet deep. This departure from the design plans during construction added about 2,500 pounds of additional concrete dead load to each pile group in excess of the design load. However, with little maintenance, this bridge stood for more than 54 years, regularly carrying heavy vehicles that exceeded the design load. Therefore, the Safety Board

⁶¹For more information, see Highway Accident Report "Collapse of a Suspended Span of Interstate Route 95 Highway Bridge Over the Mianus River, Greenwich, Connecticut, June 28, 1983." (NTSB/HAR-84/03); and Highway Accident Report "Collapse of the U.S. 43 Chickasawbogue Bridge Spans Near Mobile, Alabama, April 24, 1985." (NTSB/HAR-86/01).

concludes that it is unlikely that this additional weight contributed to the collapse. Further, the rectangular configuration of the footing may have contributed slightly to the depth of local scour as the footing first became exposed since the blunt face of the footing would have caused a slightly larger roller effect in front of the footing. However, at the time of the collapse, without local scour, the streambed was as much as 5.9 feet below the bottom of the footing. As a result, the Safety Board concludes that the rectangular configuration of the footing probably did not affect the depth of local scour that preceded the bridge collapse.

Adequacy of Design Considerations for the Southbound Bridge

When TDOT performed their hydraulic analysis for the construction of the southbound bridge, they considered the environmental backwater effects on the surrounding flood plain, and the local scour effects on the proposed bridge as a result of the flood plain constriction caused by the construction of the bridge embankments. The analysis assumed a maximum 5 fps flow velocity to determine a maximum vertical scour depth of 19 feet in the main channel. The southbound bridge was then subsequently designed to accommodate this scour. However, the hydraulic analysis for this bridge did not address the migration of the river channel. The potential lateral changes in a channel from man-induced alterations of river reaches, such as the 1974 flood plain constriction of the Hatchie River, were generally not considered during bridge design in the 1970's. Research concerning the importance of lateral migration effects and bank adjustments of channels in response to man-induced river alterations did not emerge until the early 1980's. Further, during the construction of the southbound bridge, the north bank of the river was located just south of column bent 70 of the northbound bridge. Therefore, if the bridge designers had applied the information contained in the hydraulic analysis to the condition of the northbound bridge, it is unlikely that they would have concluded that column bent 70 was potentially threatened with undermining as a result of the flood plain constriction. Although constriction of the flood plain occurred only during floods, the length and duration of the annually recurring Hatchie River flood season made the constriction effect a frequent and sustained occurrence.

The 1973 AASHTO Standard Specifications indicated that bridge designers should consider "natural stream meanders" when selecting bridge locations. While it is understandable that the TDOT designers would not have considered the lateral migration effects caused by the constriction of the flood plain, they did not compare the historical river data collected by the COE at the bridge site. Had the designers compared these data with the northbound bridge design plans, they would have discovered that the north bank of the main channel had moved northward more than 40 feet toward column bent 70. Although in 1974, column bent 70 was not yet undermined, the designers did not recognize an established pattern of channel migration and the potential for undermining of column bent 70. Therefore, the Safety Board concludes that enough information and guidance was available for the designers of the southbound bridge to have discovered the natural channel meander of the Hatchie River, and to have anticipated that further migration would undermine column bent 70 of the northbound bridge.

The current AASHTO bridge design specifications⁶² regarding bridge waterways are similar to the 1973 AASHTO design specifications used during the design of the southbound bridge. The Hydraulic Studies section of the 1989 specifications discusses the collection and evaluation of hydrologic and hydraulic information to determine the design details for a new bridge. However, the standards do not provide instructions for designers to evaluate the detrimental effects to existing bridges caused by the construction of a new bridge in the same reach of the stream. The collapse of the northbound U.S. 51 Bridge highlights how man-induced alterations in streams, such as the construction of the southbound bridge embankments, can dramatically effect existing structures. Therefore, the Safety Board believes that hydraulic and hydrologic bridge design evaluations should include an examination of geomorphic changes in the river reach caused by the construction of a new bridge, and the effects of those changes on existing structures.

Adequacy of the TDOT Bridge Inspection Program

Scope of Inspections.--The 1979, 1985, and 1987 inspection reports accurately identified the channel migration around column bent 70. The 1985 inspection report indicated that the channel had cut into the embankment at column bent 70 and 71, and in 1985, an accompanying maintenance recommendation to "Protect piers 5, 6, 7, and 70 from scour" was developed by the regional inspection engineer and forwarded with the inspection report to the SI&A section for evaluation. The 1987 inspection also indicated that there was erosion of the north bank around column bent 70, that the ground line was below the column bent 70 footing, and that underwater drift had accumulated at the column bent. The computer summary of this inspection transmitted to the SI&A section from the region also contained comments concerning the scour around column bent 70. Although there were no maintenance recommendations associated with these comments, the inspection report contained several separate indicators of scour, channel migration, and debris accumulation affecting column bent 70. As a result, the Safety Board concludes that the on-site inspections of the northbound U.S. 51 Bridge adequately identified the exposure of the column bent 70 footings and piles due to the northward migration of the Hatchie River channel.

Although the exposure of the column bent 70 footings and piles was identified in the 1987 inspection report, the bridge was only rated poor. TDOT indicated that an inspector would have to notice some settlement or leaning of a structure before it would be rated critical. As illustrated in this collapse, some simply-supported bridges are significantly effected by slight misalignment. Therefore, the Safety Board believes that TDOT should modify its bridge rating criteria to remove the requirement that a structure should show some settlement or leaning before it is rated critical.

⁶²American Association of State Highway and Transportation Officials, Standard Specifications for Highway Bridges, fourteenth edition. AASHTO, Washington, D.C., 1989.

Prior to the 1987 bridge inspection, the regional inspection office developed inspection sheets for each bridge member based on the bridge design plans. These sheets identified the bridge member configuration; however, they did not indicate dimensions. The sheets were subsequently used by the inspection team in lieu of the bridge design plans during the on-site inspection. The regional inspection engineer testified that these sheets replaced the need for on-site design plans, and that, as a result, inspection teams rarely possessed design plans when inspecting a bridge. During the 1987 inspection of the northbound U.S. 51 Bridge, the inspector measured the column bent 70 footing by feeling along its side with a rod and determined that the footing was 5 feet deep. Utilizing this 5-foot measurement, the inspector calculated that about 1 foot of the piles supporting the column bent were exposed to water. However, the bridge design plans, and the examination of the bridge wreckage by CEI divers revealed that the column bent 70 footing depth was only 3 feet. Therefore, the piles supporting column bent 70 were actually exposed about 3-feet in 1987. Although the length of exposed piles was not accurately represented on the inspection report, the undermining of the column bent 70 footing was identified, and the inspectors indicated that the column bent should be protected from scour. Further, when the regional inspection engineer reviewed the 1987 inspection report he apparently did not compare the report with the bridge design plans; had he made this comparison, the conflicting footing measurement may have been discovered.

In previous bridge collapse investigations, the Safety Board has noted that inspectors did not have adequate design or as-built plans when inspecting bridges. As a result serious deficiencies that contributed to the collapses were overlooked. The investigation of the New York Thruway Bridge collapse revealed that because the inspectors did not have design plans, they assumed that the bridge was supported by piles, when the bridge was actually supported by spread footings. Further, the investigation of the S.R. 675 Pocomoke City Bridge collapse revealed that because the inspectors did not have design or as-built plans, they were unable to determine the original diameters of the substructure piles and, therefore, did not recognize that the piles had been reduced in cross section by as much as 35 percent.

The Safety Board concludes that if bridge design or as-built plans had been available to the TDOT inspector in 1987, he may have discovered that his measurement of the column bent 70 footing was contrary to the designed footing depth. At a minimum, this may have generated more scrutiny of the exposed timber piles by the inspectors and the regional inspection engineer. Therefore, the Safety Board believes that it is essential for inspectors to have available bridge design or as-built plans during on-site bridge inspections.

Adequacy of Underwater Inspection Criteria.--Prior to the bridge collapse, TDOT had developed a program using divers to inspect underwater elements of bridges covered continuously by 10 feet or more of water. Further, at the time of the collapse, TDOT was performing underwater inspections with divers based on bridge inspector's and evaluator's recommendations. The northbound U.S. 51 Bridge had never received a diver underwater inspection, nor had one ever been recommended. TDOT indicated

that the northbound U.S. 51 Bridge was not submerged in 10 feet of water all year and, therefore, did not meet the TDOT criteria for a diver inspection. However, the 1983 AASHTO Manual for Maintenance Inspection of Bridges Section 2.4.2(3) "Piers and abutments" states: "Any exposed piling must be inspected in accordance with the acceptable procedures listed in 2.4.2(4) "Bents." In the section on bents, the manual states "This category includes timber, concrete and steel bents... Timber piles must be checked for decay,... Footing piles which have been exposed by scour below the mud line are highly vulnerable to attack." The Safety Board believes that a diver inspection is needed to adequately examine the condition of submerged timber piles that cannot be reached by bridge inspectors. Therefore, the Safety Board concludes that even though the northbound U.S. 51 Bridge did not meet the TDOT criteria to receive a diver inspection, a diver inspection of the bridge should have been conducted following the 1987 inspection because of the exposure of the untreated timber piles noted in the inspection report.

At the time of the collapse, the northbound U.S. 51 bridge had not received a diver inspection because it was submerged less than 10 feet during the late summer months; however, TDOT did not inspect the bridge during the period when the river level was lowest. During the 1987 inspection, the measured water level was 13 feet at pier 7. As a result, the Safety Board concludes that the 1987 TDOT inspection of the northbound bridge did not occur when conditions were optimum for inspectors to examine the substructure bridge elements. In April, 1990, TDOT revised their diver inspection criteria to include all bridges that had substructure members submerged more than 3.5 feet during low water. The Safety Board recognizes that this new criteria will increase the number of bridges that receive a diver underwater inspection; however, it is the Safety Board's opinion that it may not be possible to schedule each bridge for inspection during lowest water level periods. Therefore, the Safety Board believes that TDOT should expand its inspection criteria to require that submerged bridge elements, that cannot be fully examined by bridge inspectors during scheduled inspections, receive follow-up or diver inspections.

Further, as a result of the collapse of the New York Thruway Bridge near Amsterdam, New York, in 1987, the FHWA revised the NBIS to include a requirement that the inspection frequency and procedure be described for those bridges with underwater members that cannot be visually evaluated during periods of low flow or examined by feel for condition and integrity due to excessive water depth or turbidity. The Safety Board believes that the FHWA should further expand the NBIS to require follow-up or diver inspections of those members that are not examined visually, or by feel during scheduled bridge inspections due to excessive water depth or turbidity.

Use of Hydraulic and Hydrologic Information During Bridge Inspections.--
During the 1985 and 1987 inspections, TDOT inspectors measured the streambed depth surrounding each substructure element of the northbound U.S. 51 Bridge. Additionally, the COE maintained historical channel profile data for the Hatchie River at the bridge site. However, prior to the collapse, a channel profile of the river was not being maintained by TDOT. As a result, the SI&A evaluator of the 1987 inspection report used only the 1985, and 1987

inspection report measurements when evaluating the bridges relationship with the streambed, and therefore, would not have been able to determine the extent of channel migration at the bridge site.

The USGS indicated that unaltered streams in west Tennessee are often naturally meandering. Further, the 1983 AASHTO Manual for Maintenance Inspection of Bridges indicates that channel profile records should be maintained for bridges over water to determine significant changes concerning the tendency toward "scour, channel shifting, degradation, or aggradation." Although information was only emerging in the mid 1980's concerning the lateral movement of stream channels in response to man-induced channel alterations, the effects of natural stream meanders were known. Therefore, the Safety Board concludes that enough guidance and information was available in 1987 for TDOT to have recognized the need to develop and study a channel profile record for the Hatchie River at the site of the U.S. 51 Bridges. Had TDOT established a channel profile record, the SI&A evaluator for the 1987 inspection report may have recognized the lateral channel movement occurring at the bridge site, and the potential for further undermining of column bent 70. Further, since most streams naturally change configuration and flow pattern with time, the Safety Board believes that the FHWA should require States to develop and maintain channel profile records for bridges over water, and to evaluate those channel profile records to determine the effects of channel changes on bridges.

As a result of the FHWA Technical Advisory (TA) on Scour, TDOT initiated a program in September, 1988 in cooperation with the USGS to identify scour critical bridges. TDOT indicated that this program should also identify those bridges subjected to lateral channel movements. Additionally, following the collapse, TDOT began to compile channel profile records for bridges over water, and to compile a list of bridges with exposed footings and piles, and TDOT is using this information to assist regional bridge engineers with repair details for existing bridges. However, the TA recommends that States screen their existing bridges so that they can later be evaluated by an inter-disciplinary team of structural, hydraulic, and geotechnical engineers. It is the Safety Board's opinion that the program developed by TDOT in cooperation with the USGS should adequately identify those bridges that are scour critical. The Safety Board believes that TDOT should also establish an inter-disciplinary team of engineers to develop the repair and rehabilitation programs for those bridges that are determined to be scour critical. Further, the Safety Board believes that TDOT should immediately repair those bridges determined to have exposed friction piles.

Deficiencies in the Use of Inspection Data.--The 1985, and 1987 inspection reports for the northbound U.S. 51 Bridge adequately identified the undermining of the column bent 70 piles. However, apparently neither the regional inspection engineer nor the SI&A evaluator determined that this condition was critical and required immediate action, even though the 1987 field inspection report recommended that column bent 70 be protected from scour. As a result, repairs were not performed to correct the channel migration underneath column bent 70.

At the time of the collapse, changes to the NBIS and the FHWA TA concerning scour and channel migration had just recently been issued. The TDOT evaluators may not have recognized the importance or potential of scour when they reviewed the 1987 inspection report. Therefore, the Safety Board believes that TDOT personnel involved in bridge inspections should be trained in accordance with the FHWA Technical Advisory "Scour at Bridges," and other FHWA and AASHTO publications concerning the inspection of underwater bridge elements.

Further, TDOT evaluators failed to recognize the importance of the exposure of the friction piles supporting column bent 70 that was noted in the 1987 inspection report. Friction piles are dependent on the surrounding soil for their load bearing capacity, and any exposure of those piles diminishes their ability to carry the bridge loads. Although the evaluators may not have been aware of the potential magnitude of scour, they should have identified a potentially hazardous situation based on the exposed friction piles. The exposure of the friction piles may have required immediate repairs of column bent 70, or more frequent, or underwater inspections of the bridge to monitor the condition of the piles. Therefore, the Safety Board concludes that TDOT evaluators failed to identify the potential hazard to the column bent 70 piles, even though the information to make this determination was included in the 1987 bridge inspection report.

Currently, the NBIS establishes qualification requirements for the individual in charge of the State bridge inspection organization and the inspection team leaders; however, the NBIS has no qualification requirements for bridge inspection report evaluators. In 1987, the TDOT bridge inspection report evaluator failed to identify the fundamental importance of the exposure of the column bent 70 friction piles. Even though the individual in charge of the State bridge inspection organization is required to be qualified, the Safety Board believes that it is unreasonable to expect this individual to personally monitor the evaluation of each bridge inspection report. Therefore, the Safety Board believes that the FHWA should establish qualification requirements for personnel who evaluate bridge inspection reports.

Identifying and evaluating critical bridge features that could independently cause the sudden collapse of a bridge component should be paramount in any review of inspection material. This need is especially important for structurally nonredundant bridges, where the failure of a critical feature could cause not only the collapse of a bridge component, but could result in a rapid, catastrophic collapse. On July 19, 1984, the Safety Board issued Safety Recommendation H-84-50 to the Federal Highway Administration. This safety recommendation was one of 15 addressed to the FHWA as a result of the Safety Board's investigation of the collapse of a section of the Interstate Route 95 highway bridge over the Mianus River near Greenwich, Connecticut on June 28, 1983. Safety Recommendation H-84-50 asked the FHWA to:

Require each State to develop an individualized inspection procedure for each bridge under State inspection jurisdiction that has critical elements whose failure will almost certainly result in a catastrophic failure of the bridge.

The FHWA responded to this safety recommendation on November 9, 1984, by transmitting a copy of an FHWA memorandum from the FHWA Associate Administrator for Engineering and Operations to all Regional Federal Highway Administrators. The subject of the July 16, 1984 memorandum was cited as being, "Inspection and Maintenance of Major or Unusual Bridges." The memorandum contained the following directive to the Regional Federal Highway Administrators:

Each Regional Administrator, through FHWA and State highway agency channels, is directed to take appropriate measures, including contract modification if necessary, to assure that all ongoing design contracts for these types of bridges require explicit in-service inspection and maintenance guidance for bridge owners. Provision should, of course, be made for developing such guidance as part of any new design efforts for these same categories of bridges.

and further;

To provide bridge safety inspectors with additional guidance concerning the inspection and evaluation of fracture critical details of bridges, the FHWA is developing a manual on "Inspection of Fracture Critical Bridge Members" and a companion training course. The manual and course should be available in 1985. For your information, we are attaching a copy of the "Statement of Work" for the contract being awarded for this work.

Based on these efforts by the FHWA, Safety Recommendation H-84-50 was classified as "Closed--Acceptable Action" on June 10, 1985.

In further efforts on the issue of individualized bridge inspection procedures, the FHWA issued Transmittal 427 to Volume 6, Chapter 7, Section 2, Subsection 1 of the Federal-Aid Highway Program Manual. This material was issued as part of the 1989 revision to the NBIS and indicated that the individual in charge of the organizational unit that has been delegated the responsibilities for bridge inspection, reporting and inventory shall determine and designate on the individual inspection and inventory records and maintain a master list of:

Those bridges which contain fracture critical members, the location and description of such members on the bridge and the inspection frequency and procedures for inspection... Those bridges which contain unique or special features requiring additional attention during inspection to ensure the safety of such bridges and the inspection frequency and procedure for inspection of each such feature...

However, these efforts by the FHWA have been limited to the inspection of those bridge members that may be fracture critical or unusual. As a result of the Safety Board's investigation of the collapse of the northbound U.S. 51 Bridge, it is apparent that properly inspecting fracture critical bridge members is not enough to ensure the safety of a bridge. The proper evaluation of the data gathered during bridge inspections is also essential; without this evaluation, repairs in response to information obtained during the inspections may not occur. The 1987 inspection report of the northbound U.S. 51 Bridge adequately identified a condition that eventually led to the sudden collapse of the bridge; however, because the inspection report evaluator failed to recognize the critical nature of this condition, repairs were never made. Further, the Safety Board does not believe that the inspection report evaluator should alone be responsible for the identification of critical bridge features that could independently cause the sudden collapse of a bridge component. Therefore, the Safety Board believes that the FHWA should require States to develop a crucial element checklist for each bridge based on the bridge design and as-built plans, or available bridge data. The list should identify bridge elements or conditions that when damaged, exposed, corroded or deformed would independently cause a sudden unexpected collapse of a section of the bridge. This list should then become part of each bridge inspection report. Further, when an inspector discovers the deterioration of a bridge element contained in the crucial element checklist, the States should be required to immediately close the bridge or perform needed repairs.

Adequacy of Load Rating Policies.--The last TDOT load rating of the northbound U.S. 51 Bridge indicated that the bridge was capable of supporting an H-15 truck, and therefore, according to TDOT policy, did not require load posting. However, the load rating calculations did not consider the substructure bridge elements, or the actual physical condition of the substructure, nor were they required to do so. Although the load carrying capacity of column bent 70 was not determined, it is apparent that the exposure of the friction piles supporting the column bent significantly reduced their ability to support heavy loads. As illustrated by this collapse, the Safety Board believes that the bridge substructure can become a weak member of the bridge, and, therefore, should be considered in load rating procedures.

The Safety Board previously addressed the issues of load rating in its 1989 report on the Collapse of the S.R. 675 Bridge over the Pocomoke River. As a result of the investigation the Safety Board issued Recommendation H-89-72 to the American Association of State Highway and Transportation Officials:

Modify Section 4.5 "Rating of Bridges, Evaluations" to require the evaluation of substructural bridge members during load rating calculations. (H-89-72)

This safety recommendation was issued on January 9, 1990 and is currently classified as open-awaiting response.

Further, the AASHTO Manual for Maintenance Inspection of Bridges states that: "A concrete bridge need not be posted for restricted loading when it has been carrying normal traffic for an appreciable length of time and shows no distress." Although the northbound U.S. 51 bridge did not require load posting, if it had, the bridge may have been exempt from posting because of this clause. The bridge had carried normal traffic for over 55 years, and at the time of the last inspection, did not show any severe distress due to traffic loading. Although, AASHTO recommends that these concrete bridges receive more frequent inspections, the Safety Board believes that all bridges should be load rated and then appropriately posted. Simply because a bridge has not yet shown any distress from traffic does not indicate that it can safely support frequent heavy truck loads.

During the months preceding the collapse, a variety of overweight trucks (more than 80,000 lbs but less than 150,000 lbs) were permitted to travel across the northbound U.S. 51 Bridge. The I&R CEM2 testified that permit applications for vehicles weighing less than 150,000 lbs are not reviewed by the I&R Office when these vehicles cross bridges that are not load posted. Further, load posting is only required when the maximum legal load under State law (80,000 lbs in Tennessee) exceeds the bridge operating rating.⁶³ The northbound U.S. 51 Bridge was subjected to an average of 76 trucks per month that exceeded the legal load limit. Although there are no indications that successive overweight vehicle loads contributed to the collapse, the Safety Board concludes that the frequency with which these vehicles traveled across the bridge was potentially harmful to the structure. Therefore, the Safety Board believes that States should establish review procedures for overweight vehicles, to evaluate the effects of frequent overweight loads on unposted bridges. Further, based on this evaluation, the States should then limit the number and size of overweight vehicles permitted to cross those bridges that may be damaged because of frequent exposure to heavy loads.

Further, the TDOT permit office did not obtain weight per axle or axle spacing information, for overweight vehicles under 150,000 pounds, when issuing overweight permits. This information is essential to accurately assess the damage an overweight vehicle can cause to a bridge. Therefore, the Safety Board believes that TDOT should obtain weight per axle and axle spacing information for overweight vehicles when issuing overweight permits.

TDOT Organizational Structure Before and After the Collapse

Following the collapse, TDOT modified their organizational structure regarding bridge inspection and maintenance. The consolidation of regional maintenance and bridge inspection activities under the direction of a regional bridge engineer will likely result in closer coordination of maintenance in response to recommendations. However, the I&R CEM2 testified that the flow of the bridge inspection reports regarding their evaluation would remain the same. The Safety Board believes that changes to the NBIS,

⁶³The absolute maximum permissible load to which the structure may be subjected.

and the scour studies that TDOT has initiated have improved their ability to identify scour and channel migration at bridges; however, it remains incumbent on the SI&A evaluator to detect potential scour based on the bridge inspection reports. Once the evaluator determines that the potential for scour exists at a bridge, he can request additional inspections or evaluations from the HS Office, or recommend several methods to notify the TDOT maintenance forces to close, load post, or repair the bridge. Additionally, once the evaluator determines that action is necessary, his decision is reviewed by his supervisor within the SI&A section. However, if the evaluator determines, based on the bridge inspection report, that action is not needed to correct or prevent scour, there is no further review. The evaluator of the 1987 northbound U.S. 51 Bridge inspection report apparently did not identify the need for immediate action to correct or protect the bridge from scour. As a result, in 1987, the Regional Engineer received only a maintenance recommendation concerning a potential scour problem at the bridge site. The Safety Board believes that since the biennial bridge inspection reports are the primary source used to detect deficiencies in a bridge, TDOT should ensure that those reports that identify potential scour or channel migration are further reviewed by hydraulic engineers.

As a result of the 1985 TDOT inspection of the northbound U.S. 51 Bridge, maintenance recommendations to protect column bent 70 from scour were issued to the region 4 director. During the Safety Board's public hearing the region 4 director testified that because of budget and manpower constraints, less than 50 percent of the annual computer transmitted maintenance recommendations were accomplished. Therefore, the Safety Board concludes that because TDOT did not have sufficient resources to accomplish the majority of the maintenance recommendations, they missed the opportunity to correct the channel migration beneath column bent 70, or protect column bent 70 from scour, through routine preventive maintenance. Accordingly, the Safety Board believes that TDOT should provide maintenance resources necessary to accomplish maintenance recommendations developed as a result of bridge inspections.

Although no maintenance was ever performed in response to the 1985 recommendations concerning scour, minor maintenance such as drainage work, and asphalt patching was accomplished for the bridge. If the maintenance recommendations had been prioritized in 1985, it is likely that the recommendation concerning scour would have received greater attention, and some maintenance may have been performed in response to the recommendation. Although, as a result of TDOT's modification to their organization, bridge maintenance and bridge inspection activities are now directed by each regional bridge engineer, there still is no priority ranking system for maintenance recommendations. The Safety Board believes that maintenance at all levels should be prioritized and, therefore, TDOT should establish a priority ranking system for maintenance recommendations issued as the result of bridge inspections.

FHWA Bridge Management Program

The Safety Board believes that the overriding concern of bridge owners should be to repair or close those bridges that are in imminent danger of collapse. The FHWA bridge management system concept addresses these critical bridges during the priority ranking of bridges for rehabilitation or repair. However, bridge management systems primarily assist the States in administering the limited funding for bridge rehabilitation and maintenance over the network of bridges within their jurisdiction. The collection of the necessary data, and its evaluation within a priority ranking formula could be a lengthy process. Even though the Safety Board recognizes the importance of establishing a bridge management system, the States should not rely on the bridge management priority ranking to identify safety deficient bridges before action is taken. Bridges that are in imminent danger of collapse should be identified by the States by other means (inspection data, special features evaluation, etc.) as soon as possible. The FHWA should require the identification, and then closing or repair, of those bridges prior to instituting a repair/rehabilitation priority schedule based on the bridge management philosophy. Once, this has been done, the priority ranking can act as a fail safe mechanism to discover those bridges that may not have been previously identified as critical.

CONCLUSIONS

Findings

1. The passenger car drivers and truck driver were unable to avoid the accident.
2. The post-collapse emergency response could not have reduced the severity of this accident.
3. Column bent 71 and span 79 were still standing following the collapse of column bent 70 and spans 77 and 78.
4. The west column of column bent 71 was fractured, and the entire column bent and span 79 subsequently collapsed, as a result of successive impacts from the accident vehicles.
5. The deterioration of the exterior superstructure girders of spans 77, 78, and 79 did not contribute to the bridge collapse.
6. It is unlikely that a fracture of the concrete members of column bent 70 initiated the collapse sequence.
7. It is unlikely that the piles buckled as a result of a reduction in the pile cross-sections.
8. Column bent 70 failed most likely from the embedment of the supporting timber piles, perhaps in combination with pile buckling, due to their exposure from a combination of channel migration and local scour.

9. The simply-supported spans of the northbound U.S. 51 Bridge allowed the collapse to occur with little warning over a short period of time.
10. It is unlikely that the additional weight of the concrete footings contributed significantly to the collapse.
11. Because of the streambed elevation at the time of the collapse, the rectangular configuration of the footing probably did not effect the depth of local scour.
12. Enough information and guidance was available for the designers of the southbound bridge to have discovered the natural channel meander of the Hatchie River, and to have anticipated that further migration would undermine column bent 70 of the northbound bridge.
13. The on-site inspections of the northbound U.S. 51 bridge adequately identified the exposure of the column bent 70 footings and piles because of the northward migration of the Hatchie River channel.
14. Had bridge design or as-built plans been available to the TDOT inspector in 1987, he may have discovered that his measurement of the column bent 70 footing was contrary to the designed footing depth.
15. Even though the northbound U.S. 51 Bridge did not meet the TDOT criteria to receive a diver inspection, a diver inspection of the bridge should have been conducted following the 1987 inspection because of the exposure of the timber piles noted in the inspection report.
16. The 1987 TDOT inspection of the northbound bridge did not occur when conditions were optimum for inspectors to examine the substructure bridge elements.
17. Enough guidance and information was available in 1985 and 1987 for TDOT to have recognized the need to develop and study a channel profile record for the Hatchie River at the site of the U.S. 51 Bridge.
18. Neither the TDOT regional inspection engineer nor the Structures Inventory and Appraisals evaluator determined that the undermining of column bent 70 was critical and required immediate action, even though the 1985 and 1987 field inspection reports recommended that the column bent be protected from scour.
19. TDOT evaluators did not recognize the importance or potential of scour when they reviewed the 1985 or 1987 inspection reports.
20. TDOT evaluators failed to recognize the potential hazard caused by the exposure of the friction piles supporting column bent 70, even though the information to make this determination was included in the 1987 Bridge Inspection report.

21. The frequency with which overweight vehicles were permitted to travel across the bridge was potentially harmful to the structure.
22. Because TDCT did not have sufficient resources to accomplish the majority of the maintenance recommendations, they missed the opportunity to correct the channel migration beneath column bent 70, or protect column bent 70 from scour, through routine preventive maintenance.

Probable Cause

The National Transportation Safety Board determines that the probable cause of the collapse of the northbound U.S. Route 51 Bridge spans was the northward migration of the main river channel which the Tennessee Department of Transportation failed to evaluate and correct. Contributing to the severity of the accident was the lack of redundancy in the design of the bridge spans.

RECOMMENDATIONS

As a result of its investigation, the National Transportation Safety Board recommends:

--to the Federal Highway Administration:

Modify the National Bridge Inspection Standards to require follow-up or diver inspections of those bridges with underwater members that cannot be examined visually, or by feel during scheduled bridge inspections because of excessive water depth or turbidity. (Class II, Priority Action)(H-90-56)

Require States to develop and maintain channel profile records for bridges over water, and to evaluate the channel profile records to determine the effects of channel changes on bridges. (Class II, Priority Action)(H-90-57)

Modify the National Bridge Inspection Standards to require qualifications for personnel who evaluate bridge inspection reports. (Class II, Priority Action)(H-90-58)

Require States to develop a crucial element checklist for each bridge based on the bridge design and as-built plans, or available bridge data. The list should identify bridge elements or conditions that when damaged, exposed, corroded or deformed would independently cause a sudden unexpected collapse of a section of the bridge. This list should then become part of each bridge inspection report. Further, require the States to immediately close the bridge or perform needed repairs when an inspector discovers the deterioration of a bridge element contained in the crucial element checklist. (Class II, Priority Action)(H-90-59)

Require that States review overweight vehicle traffic, to evaluate the effects of frequent overweight loads on unposted bridges. Require that, based on these evaluations, the States limit the number or size of overweight vehicles permitted to cross those bridges that may be damaged because of frequent exposure to heavy loads. (Class II, Priority Action)(H-90-60)

--to the American Association of State Highway and Transportation Officials:

Modify Section 1.3.2, "Hydraulic Studies" of the Standard Specifications for Highway Bridges to include evaluations of geomorphic changes in streams caused by the construction of a new bridge, and the effects of those changes on existing structures. (Class II, Priority Action)(H-90-61)

Modify section 2.3, "Frequency and Level of Inspection" of the Manual for Maintenance Inspection of Bridges to include a requirement that bridge inspectors be provided with available bridge design or as built plans during on-site bridge inspections. (Class II, Priority Action)(H-90-62)

Modify section 4.6, "Rating of Bridges, Limiting Vehicle Weights" of the Manual for Maintenance Inspection of Bridges to delete the section which exempts certain concrete bridges from load posting. (Class II, Priority Action)(H-90-63)

--to the Tennessee Department of Transportation:

Modify TDOT bridge rating criteria to remove the requirement that a structure show some settlement or leaning before it is rated critical. (Class II, Priority Action)(H-90-64)

Modify bridge inspection procedures to provide inspectors with available bridge design or as-built plans during on-site bridge inspections. (Class II, Priority Action)(H-90-65)

Expand TDOT bridge inspection criteria to require that submerged bridge elements, that cannot be fully examined by bridge inspectors during scheduled inspections, receive follow-up or diver inspections. (Class II, Priority Action)(H-90-66)

Establish an inter-disciplinary team of geotechnical, hydraulic, and structural engineers to develop the repair and rehabilitation programs for those bridges that are determined to be scour-critical. (Class II, Priority on)(H-90-67)

Immediately repair those bridges determined to have exposed friction piles. (Class II, Priority Action)(H-90-68)

Train TDOT personnel involved in bridge inspections to evaluate scour, in accordance with the FHWA Technical Advisory "Scour at Bridges" and other FHWA and AASHTO publications concerning the inspection of underwater bridge elements. (Class II, Priority Action)(H-90-69)

Modify bridge inspection report review procedures to require that hydraulic engineers review and evaluate all bridge inspection reports which identify the presence of scour or channel migration; and emphasize the identification and correction of channel movements and scour. (Class II, Priority Action)(H-90-70)

Obtain weight per axle and axle spacing information for overweight vehicles when issuing overweight permits. (Class II, Priority Action)(H-90-71)

Establish a priority ranking system for maintenance recommendations issued as the result of bridge inspections. (Class II, Priority Action)(H-90-72)

--to the State of Tennessee:

Provide Maintenance resource necessary to complete recommended repairs developed as a result of bridge inspections. (Class II, Priority Action)(H-90-73)

As a result of its investigation of this accident, the National Transportation Safety Board reiterates Safety Recommendation H-89-72 to the American Association of State Highway and Transportation Officials:

Modify Section 4.5 "Rating of Bridges, Evaluations" of the Manual for Maintenance Inspection of Bridges to require the evaluation of substructural bridge members during load rating calculations. (H-89-72)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

/s/ JAMES L. KOLSTAD
Chairman

/s/ SUSAN M. COUGHLIN
Acting Vice Chairman

/s/ JOHN K. LAUBER
Member

June 5, 1990

Jim Burnett, Member, filed the following dissenting statement:

I believe that the Safety Board should neither issue the final report nor adopt the probable cause of the accident until our investigators have the opportunity to study the bridge wreckage which has yet to be retrieved from the Hatchie River. Until such retrieval, the Board's report may be reviewed as premature.

The Safety Board is supposed to investigate highway accidents in cooperation with the 50 states, and the State of Tennessee specifically requested that the Board "delay the issuance of the final report until the coffer dam investigation is complete and all the facts are verified." In fact, the State of Tennessee went on record as "officially protesting" our release of this accident report. The State of Tennessee undertook to recover the bridge structure with substantial expense of Federal aid money at the urging of Safety Board investigators.

Because of the delay in the State of Tennessee's salvage operation due to high water conditions, NTSB investigators were not able to examine critical elements in the bridge structure. Consequently, our investigators could not examine, for example, the bent cap and were only able to examine a very small portion of a single timber friction pile segment that was retrieved by divers.

In addition, because our investigators have not as yet had access to the bridge wreckage still under water, we do not know the actual lengths of the friction piles. If the piles should happen to be longer than the length specified for them by the bridge design, then settlement might in fact not have occurred, in which case another failure mechanism might have occurred.

In short, I believe that the final report and probable cause are based too much on circumstantial evidence and not enough on good in-depth investigation, which is a precedent that the Safety Board does not need to set. I support the release of the safety recommendations. I do not believe that the needs of transportation safety require haste as to the determination of probable cause.

/s/ JIM BURNETT
MEMBER

June 21, 1990

APPENDIXES

APPENDIX A

INVESTIGATION AND HEARING

Investigation

The National Transportation Safety Board was notified of this accident on April 1, 1989, by the news media. Investigators were dispatched from the Washington, D.C. Headquarters and arrived on the scene on April 2, 1989.

Participating in the investigation were representatives from the Tennessee Department of Transportation, the Federal Highway Administration, and the United States Geological Survey. The Safety Board was further assisted on-scene by the Tennessee Highway Patrol, the Tennessee Emergency Management Agency, and the Covington, Tennessee Fire Department. The Safety Board commissioned several studies and tests from the United States Geological Survey, Collins Engineers Inc., and the Department of Agriculture Forest Products Laboratory to determine the events and conditions surrounding the collapse. Further, the Safety Board will participate in the examination of the submerged bridge wreckage when it is extracted from the river, to further clarify the events and conditions surrounding the collapse.

Hearing

The Safety Board convened a public hearing in Memphis, Tennessee, from November 28 to November 30, 1989, to inquire further into the bridge collapse.

APPENDIX B

VEHICLE AND OCCUPANT INFORMATION

Abbreviated Injury Scale (AIS)⁶⁴ Table

	Drivers	Passengers	Total
Maximum Injury, Virtually Unsurvivable (AIS-6)	4	3	7
Moderate (AIS-2)	$\frac{1}{5}$	$\frac{0}{3}$	$\frac{1}{8}$
Total			

A. 1978 Pontiac Bonneville 4-door sedan, green.

A post mortem examination of the 39 year old male driver of this vehicle revealed that the probable cause of death was "massive head injuries." According to the THP, this victim was found unrestrained in the drivers seat of his vehicle. This vehicle was also occupied by an unrestrained 25 year old female passenger who was found in the right front seat, and by a 4 year old female passenger who was found in the mid-front seat. The 4 year old was not restrained by either a lap belt or child restraint. A post mortem examination of both female passengers revealed that the probable cause of death was "massive head injuries."

B. 1987 Toyota Tercel 2-door sedan, gray.

A post mortem examination of the 49 year old male driver of this vehicle revealed that the probable cause of death was "multiple severe injuries, including massive head injuries." According to the THP, this victim was found unrestrained in the drivers seat of his vehicle. This vehicle was also occupied by an unrestrained 45 year old female passenger found in the right front seat. A post mortem examination of this victim revealed that the probable cause of death was "massive head injuries."

C. 1983 Ford LTD 4-door sedan, gray.

A post mortem examination of the 45 year old female driver of this vehicle revealed that the probable cause of death was "multiple injuries, including massive head injuries." According to the THP, this victim was found unrestrained in the drivers seat of her vehicle.

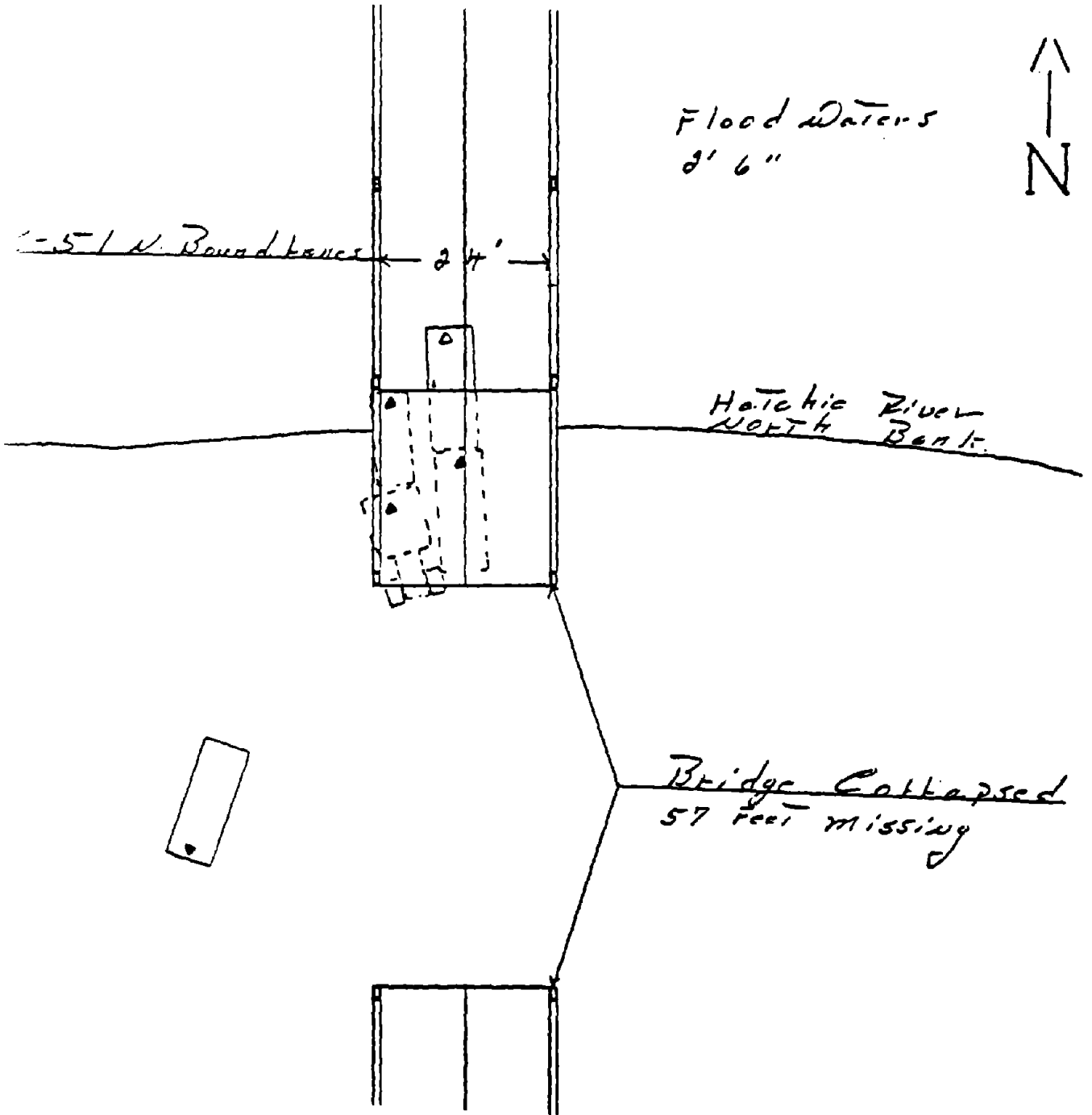
⁶⁴The 1985 revised Abbreviated Injury Scale of the Association for the Advancement of Automotive Medicine.

D. 1983 Dodge Aries Station Wagon, gray.

A post mortem examination of the 26 year old male driver of this vehicle revealed that the probable cause of death was "multiple fractures and possible drowning." According to the THP, this victim was found unrestrained in the drivers seat of his vehicle.

E. 1990 International Series 8300 3-axle tractor, red, in combination with a 1978 Great Dane 2-axle 45-foot box trailer loaded with major kitchen appliances.

A post mortem examination of the 49 year old male driver of this vehicle revealed that the probable cause of death was " multiple severe injuries, including massive head injuries." According to the THP, this victim was found unrestrained in the drivers seat of his vehicle.



Courtesy of the
Tennessee Highway Patrol

APPENDIX C

NATIONAL BRIDGE INSPECTION STANDARDS

CODE OF FEDERAL REGULATIONS

23 HIGHWAYS - PART 650

Subpart C - National Bridge
Inspection
Standards§650.301 Application of
standards.

The National Bridge Inspection Standards in this part apply to all structures defined as bridges located on all public roads. In accordance with the AASHTO (American Association of State Highway and Transportation Officials) Transportation Glossary, a "bridge" is defined as a structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet between undercopings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening.

§650.303 Inspection
procedures.

(a) Each highway department shall include a bridge inspection organization capable of performing inspections, preparing reports, and determining ratings in accordance with the provisions of the AASHTO Manual² and the Standards contained herein.

(b) Bridge inspectors shall meet the minimum qualifications stated in §650.307.

(c) Each structure required to be inspected under the Standards shall be rated as to its safe load carrying capacity in accordance with Section 4 of the AASHTO Manual. If it is determined under this rating procedure that the maximum legal load under State law exceeds the load permitted under the Operating Rating, the bridge must be posted in conformity with the AASHTO Manual or in accordance with State law.

(d) Inspection records and bridge inventories shall be prepared and maintained in accordance with the Standards.

(e) The individual in charge of the organizational unit that has been delegated the responsibilities for bridge inspection, reporting and inventory shall determine and designate on the individual inspection and inventory records and maintain a master list of the following:

(1) Those bridges which contain fracture critical members, the location and description of such members on the bridge and the inspection frequency and procedures for inspection of such members. (Fracture critical members are tension members of a bridge whose failure will probably cause a portion of or the entire bridge to collapse.)

(2) Those bridges with underwater members which cannot be visually evaluated during periods of low flow or examined by feel for condition, integrity and safe load capacity due to excessive water depth or turbidity. These members shall be described, the inspection frequency stated, not to exceed five years, and the inspection procedure specified.

(3) Those bridges which contain unique or special features requiring additional attention during inspection to ensure the safety of such bridges and the inspection frequency and procedure for inspection of each such feature.

(4) The date of last inspection of the features designated in paragraphs (e)(1) through (e)(3) of this section and a description of the findings and follow-up actions, if necessary, resulting from the most recent inspection of fracture critical details, underwater members or special features of each so designated bridge.

§650.305 Frequency of
inspections.

(a) Each bridge is to be inspected at regular intervals not to exceed 2 years in accordance with Section 2.3 of the AASHTO Manual.

The "AASHTO Manual" referred to in this part is the "Manual for Maintenance Inspection of Bridges 1983" together with subsequent interim changes or the most recent version of the AASHTO manual published by the American Association of State Highway and Transportation Officials. A copy of the Manual may be examined during normal business hours at the office of each Division Administrator of the Federal Highway Administration, at the office of each Regional Federal Highway Administrator, and at the Washington Headquarters of the Federal Highway Administration. The addresses of these document inspection facilities are set forth in Appendix D to Part 7 of the regulations of the Office of the Secretary (40 CFR Part 7). In addition, a copy of the Manual may be secured upon payment in advance by writing to the American Association of State Highway and Transportation Officials, 444 N. Capitol Street, N.W., Suite 225, Washington, D.C. 20001.

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(b) Certain types or groups of bridges will require inspection at less than 2-year intervals. The depth and frequency to which bridges are to be inspected will depend on such factors as age, traffic characteristics, state of maintenance, and known deficiencies. The evaluation of these factors will be the responsibility of the individual in charge of the inspection program.

(c) The maximum inspection interval may be increased for certain types or groups of bridges where past inspection reports and favorable experience and analysis justifies the increased interval of inspection. If a State proposes to inspect some bridges at greater than the specified 2-year interval, the State shall submit a detailed proposal and supporting data to the Federal Highway Administrator for approval.

§650.307 Qualifications of personnel.

(a) The individual in charge of the organizational unit that has been delegated the responsibilities for bridge inspection, reporting, and inventory shall possess the following minimum qualifications:

(1) Be a registered professional engineer; or

(2) Be qualified for registration as a professional engineer under the laws of the State; or

(3) Have a minimum of 10 years experience in bridge inspection assignments in a responsible capacity and have completed a comprehensive training course based on the, "Bridge Inspector's Training Manual", which as been developed by a joint Federal-State task force, and subsequent additions to the manual.²

(b) An individual in charge of a bridge inspection team shall possess the following minimum qualifications:

(1) Have the qualifications specified in paragraph (a) of this section; or

(2) Have a minimum of 5 years experience in bridge inspection assignments in a responsible capacity and have completed a comprehensive training course based on the "Bridge Inspector's Training Manual", which has been developed by a joint Federal-State task force.

(3) Current certification as a Level III or IV Bridge Safety Inspector under the National Society of Professional Engineer's program for National Certification in Engineering Technologies (NICET)³ is an alternative acceptable means for establishing that a bridge inspection team leader is qualified.

§650.309 Inspection report.

The findings and results of bridge inspections shall be recorded on standard forms. The data required to complete the forms and the functions which must be performed to compile the data are contained in Section 3 of the AASHTO Manual.

²The "Bridge Inspector's Training Manual" may be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

³The following publications are supplements to the "Bridge Inspector's Training Manual": "Bridge Inspector's Manual for Movable Bridges," 1977, GPO Stock No. 050-002-00103-5; "Culvert Inspector's Training Manual," July 1986, GPO Stock No. 050-001-0030-7; and "Inspection of Fracture Critical Bridge Members," 1986, GPO Stock No. 050-001-00302-3.

§650.311 Inventory.

(a) Each State shall prepare and maintain an inventory of all bridge structures subject to the Standards. Under these Standards, certain structure inventory and appraisal data must be collected and retained within the various departments of the State organization for collection by the Federal Highway Administration as needed. A tabulation of this data is contained in the structure inventory and appraisal sheet distributed by the Federal Highway Administration as part of the Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (Coding Guide) in January of 1979. Reporting procedures have been developed by the Federal Highway Administration.

(b) Newly completed structures, modification of existing structures which would alter previously recorded data on the inventory forms or placement of load restriction signs on the approaches to or at the structure itself shall be entered in the State's inspection reports and the computer inventory file as promptly as practical, but no later than 90 days after the change in the status of the structure for bridges directly under the State's jurisdiction and no later than 180 days after the change in status of the structure for all other bridges on public roads within the State.

³For information on NICET program certification contact: National Institute for Certification in Engineering Technologies, 1420 King Street, Alexandria, Virginia 22314. Attention: John D. Antrim, P.E., Phone (703) 684-2835.

APPENDIX D

STRUCTURE AND APPRAISAL CONDITION RATINGS FOR THE NORTHBOUND U.S. 51 BRIDGE

The numerical condition ratings prior to 1978 were defined as:

- 9 - New condition.
- 8 - good condition - no repairs necessary.
- 7 - minor items in need of repairs by maintenance forces.
- 6 - major items in need of repair by maintenance forces.
- 5 - major repairs - contract needs to let.
- 4 - minimum adequacy to tolerate present traffic - immediate rehabilitation necessary to keep open.
- 3 - inadequacy to tolerate present heavy load - warrants closing bridge to trucks.
- 2 - inadequacy to tolerate any live load - warrants closing bridge to all traffic.
- 1 - bridge repairable, if desirable to reopen traffic.
- 0 - bridge conditions beyond repair - danger of immediate collapse.

Prior to 1978, the coding system for the appraisal rating was different from the condition rating. The appraisal ratings were:

- 9 - Conditions superior to present desirable criteria.
- 8 - Conditions equal to present desirable criteria.
- 7 - Condition better than present minimum criteria.
- 6 - Condition equal to present minimum criteria.
- 5 - Condition somewhat better than minimum adequacy to tolerate being left in place as is.
- 4 - Condition meeting minimum tolerable limits to be left in place as is.
- 3 - Basically intolerable condition requiring high priority of replacement.
- 2 - Basically intolerable condition requiring high priority of repair.
- 1 - Immediate repair necessary to put back in service.
- 0 - Immediate replacement necessary to put back in service.

In 1978 the condition and appraisal ratings changed: The ratings were:

- 9 - No change - new condition.
- 8 - Good condition - no repairs needed.
- 7 - Generally good condition - potential exists for major maintenance.
- 6 - Fair condition - potential exists for major maintenance.
- 5 - Generally fair condition - potential exists for minor rehabilitation.
- 4 - Marginal condition - potential exists for major rehabilitation.
- 3 - Poor condition - repair or rehabilitation required immediately.

- 2 - Critical condition - the need for repair or rehabilitation is urgent. Facility should be closed until the indicated repair is complete.
- 1 - Critical condition - facility is closed. Study should determine the feasibility for repair.
- 0 - Critical condition - facility is closed and is beyond repair.

Structure Inventory and Appraisal ratings for the Northbound U.S. 51 Bridge

Date of report	9/75	4/77	6/79	4/81	6/83	7/85	9/87
<u>Condition Rating</u>							
Deck	7	7	6	6	5	4	5
Superstructure	4	5	5	5	5	3	4
Substructure	4	5	6	5	4	3	4
Channel and channel protection	6	7	7	7	7	7	7
Estimated remaining life (years)	30	28	10	10	10	15	8
Operating rating (HS)	58T	32T	58T	32T	32T	32T	32T
Approach roadway alignment	7	7	7	7	7	7	6
Inventory rating (HS)	38T	19T	39T	19T	19T	19T	19T
<u>Appraisal Rating</u>							
Structure condition	5	5	6	5	5	5	3
Deck geometry	2	6	4	3	3	3	3
Safe load capacity	8	8	8	5	5	5	4
Waterway adequacy	8	8	6	7	7	7	6
Approach roadway alignment	7	6	7	7	7	7	6
Cost of improvements (in \$1,000.)	6884	0	0	21000	21000	21000	21000
Sufficiency rating	52.3	39.5	48.3	35.5	20.5	7.0	16.5

APPENDIX E

DISTRIBUTION LIST OF OVERWEIGHT PERMIT VEHICLES FOR MARCH 1 TO APRIL 1, 1989.

A distribution of weights, number of axles, and by length were developed. The lengths were based on span lengths of 28.5 feet. Two sets of tables were developed, one set for permits valid on April 1 and one set for the entire month.

Permits valid April 1, 1989

Weight (pounds)	Number of axles							Total	
	5	6	7	8	9	10	11		Not indicated
80,000-89,999	1	5							6
90,000-99,999	2	3	1						6
100,000-109,999	1	2	1						4
110,000-119,999		9	1	1					11
120,000-129,999		2	1		1				4
130,000-139,999				1					1
140,000-149,999					1	1			2
150,000					1	1			2
Totals	4	21	4	2	3	2			36

Weight (pounds)	Length of truck in spans			Total
	3	4	Not indicated	
	57-85.5'	85.6-114'		
80,000-89,999	3	1	2	6
90,000-99,999	4	2		6
100,000-109,999	4			4
110,000-119,999	9		2	11
120,000-129,999	2	1	1	4
130,000-139,999		1		1
140,000-149,999		2		2
150,000	1	1		2
Total	23	8	5	36

Permits issued between March 1 to April 1, 1989

Weight	Number of axles							Total	
	5	6	7	8	9	10	11		Not indicated
80,000-89,999	10	7							17
90,000-99,999	8	15	1						24
100,000-109,999	7	14	2	1					24
110,000-119,999		18	1	1					24
120,000-129,999		3	7	2	1				13
130,000-139,999			3	6					9
140,000-149,999			1	2	4	4	1		7
150,000					4	1	1	1	7
Totals	25	57	15	12	9	5	2	1	126

Permits issued between March 1 to April 1, 1989

	Length of truck in spans			Total
	3	4	Not indicated	
	57-85.5'	85.5-114'		
80,000-89,999	7	2	8	17
90,000-99,999	9	5	10	24
100,000-109,999	9		15	24
110,000-119,999	15	1	4	20
120,000-129,999	9	1	3	13
130,000-139,999	5	4		9
140,000-149,999	3	9		12
150,000	1	6		7
Totals	58	28	40	126

APPENDIX F

TYPICAL HIGHWAY BRIDGE STRUCTURE, EXPLODED VIEW.

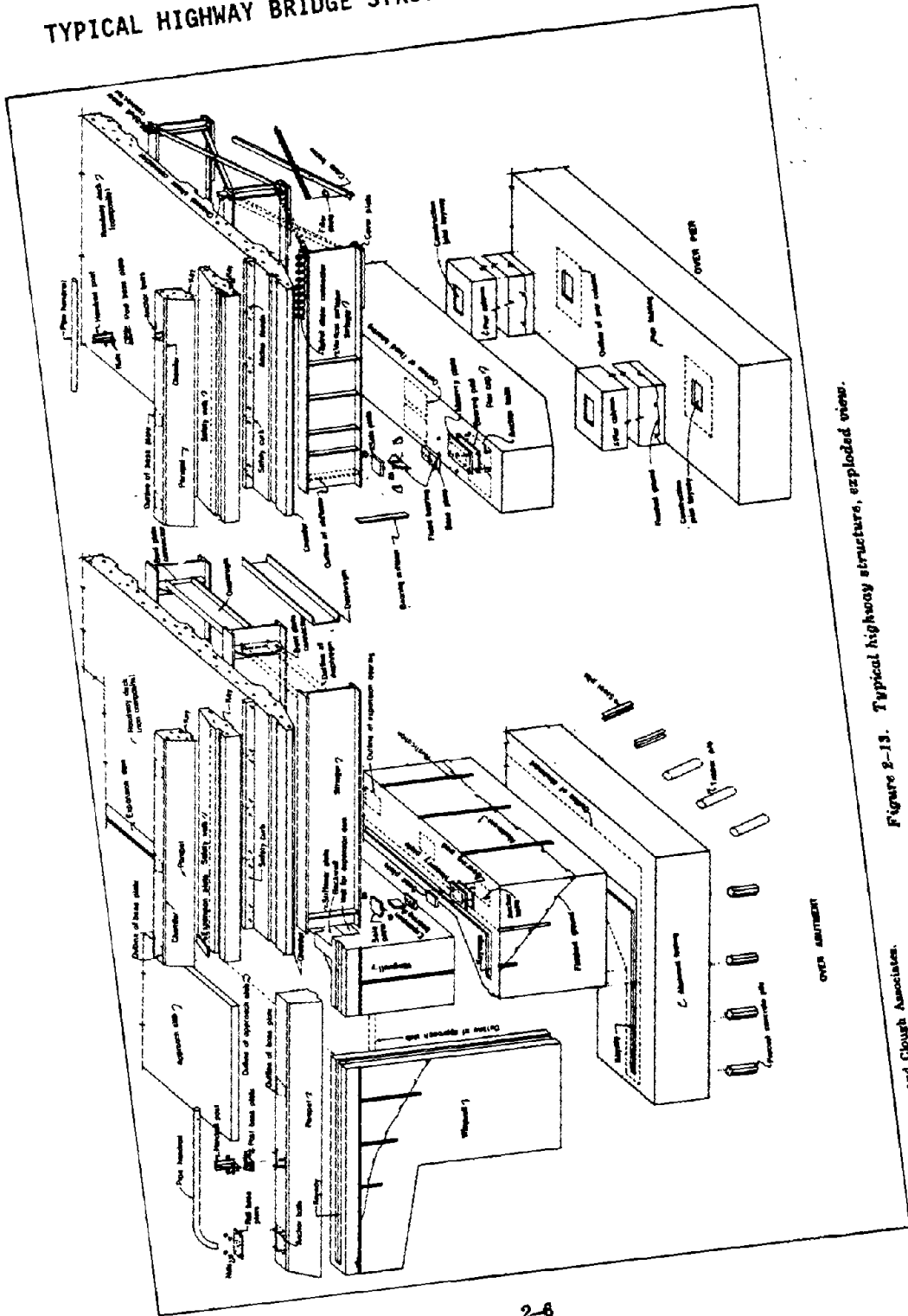


Figure 2-13. Typical highway structure, exploded view.

Courtesy of Clarkson and Clough Associates.

