National Transportation Safety Board

Office of Highway Safety

Washington, DC 20594

DCA24MM031

BRIDGE PROTECTION SYSTEMS

Group Chair's Factual Report

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Location: Baltimore, Maryland
Date: March 26, 2024
Time: 1:29 a.m. EST

B. BRIDGE PROTECTION SYSTEMS GROUP

Group Co-Chairs	Dan Walsh Highway Factors Investigator NTSB - HWY
	Scott Parent Highway Factors Investigator NTSB - HWY
Group Member	Derek Soden, P.E., S.E. Principal Structural Engineer - Team Leader Federal Highway Administration
	Jim Harkness, P.E., PTOE Chief Engineer Maryland Transportation Authority
	Eric Gregson Technical Reconstructionist NTSB - HWY
	Adrienne Lamm Materials Engineer NTSB - RE

C. BRIDGE COLLAPSE SUMMARY

On March 26, 2024, about 0129 eastern daylight time, the 984-foot-long Singapore flagged cargo vessel (containership) *Dali* was transiting out of Baltimore Harbor in Baltimore, Maryland, when it experienced a loss of electrical power and propulsion and struck the southern pier (Pier 17) supporting the central truss spans of the Francis Scott Key Bridge (Key Bridge). A portion of the bridge subsequently collapsed into the river, and portions of the deck and the truss spans collapsed onto the vessel's forward deck. A seven-person road maintenance crew employed by Brawner Builders—which was contracted by the Maryland Transportation Authority (MDTA)—and one inspector employed by Eborn Enterprises, Inc., a subconsultant to the MDTA, were on the bridge when the vessel struck it. The inspector escaped unharmed, and one of the construction crewmembers survived with serious injuries. The bodies of the six fatally injured construction crewmembers were recovered. One of the 23 persons aboard the *Dali* was injured.

D. DETAILS OF THE BRIDGE COLLAPSE

The Bridge Protection Systems Group Chair's Factual Report begins with a general discussion on the description of the Key Bridge. The report provides an in-depth discussion on the risk assessment for the Key Bridge using the American Association of State Highway and Transportation Officials (AASHTO) Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges. The report provides a description of the bridge protection systems including the fender system, dolphins, owner's responsibility for bridge pier protection, and navigation channel.[1] The report summarizes the construction activities on the Key Bridge at the time of the bridge collapse. The report documents the history of vessel collisions with the Key Bridge and protections systems on other bridges owned by the Maryland Transportation Authority (MDTA). In addition, the report summarizes interviews conducted by NTSB investigators. Finally, the report concludes with research conducted on previous bridge collapses investigated by the NTSB and the new physical protection system for the Delaware Memorial Bridge near Wilmington, Delaware.

E. BRIDGE DATA

1.0 Bridge Collapse Location

The bridge collapse occurred on the Key Bridge which carried Maryland 695 (MD 695) over the Patapsco River following a collision by the *Dali*, which was transiting out of the Baltimore Harbor in a southeast direction toward the bridge.

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[1] Dolphins are large diameter circular sheet pile cells filled with sand or concrete to protect bridge piers.

Figure 1 is a map that illustrates the location of the collapse which was approximately 7 miles southeast of Baltimore, Maryland.

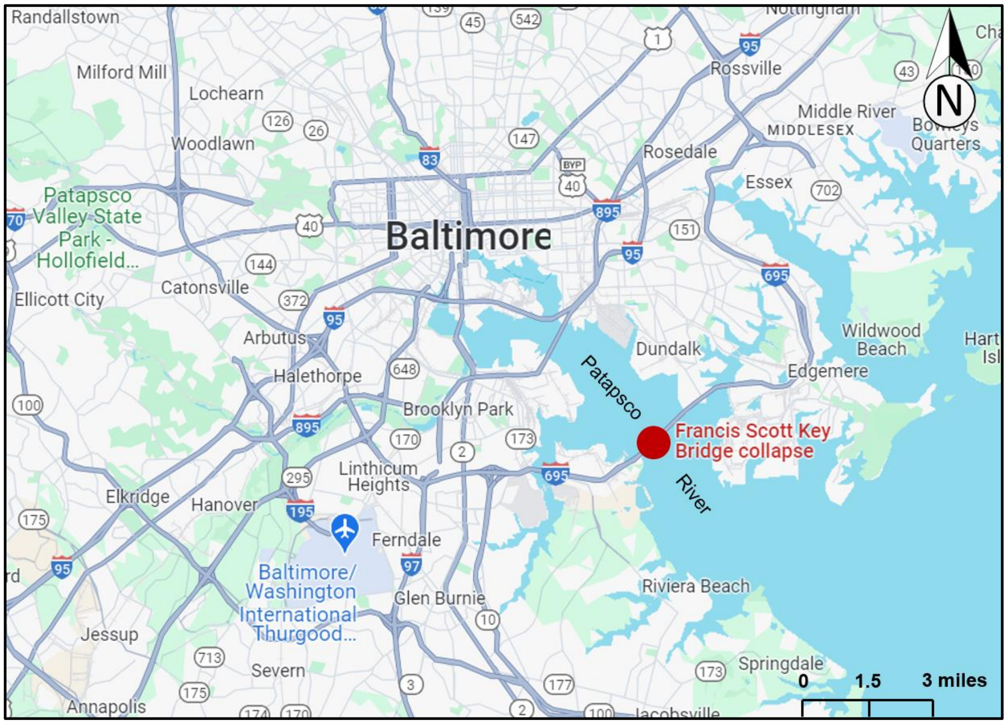

Figure 1: Bridge collapse location map (source: Google Maps revised).

2.0 Bridge Description

The Key Bridge was permitted in 1972 and opened to traffic on March 23, 1977. According to the MDTA 2023 Main BIN Biennial Inspection Report,[2] the overall length of the bridge was approximately 9,086 feet between the centerline bearings of the north and south abutments.[3] The Key Bridge consisted of the substructure, the superstructure, and physical protection systems (dolphins and fender systems).[4] The maximum vertical clearance between the mean high water (MHW)[5] and the Key Bridge within the main navigational channel was 185 feet. The overall width of the bridge was 61-feet-2-inches, while the curb-to-curb width was 58 feet, which included a 2-foot-wide median barrier.

There were four lanes, two for each direction of travel. The bridge was not posted for any load restrictions. According to data received from MDTA, the annual average daily traffic (AADT) for calendar year 2023 was 34,121 vehicles per day, and the percentage of trucks on the bridge was 10 percent. The bridge was owned and maintained by the MDTA.

[2] See Bridge Protection Systems Attachment – MDTA 2023 Main BIN Biennial Inspection Report.
[3] See Bridge Protection Systems Attachment - NTSB Horizontal and Vertical Alignments.
[4] The dolphins were independent of the bridge structure.
[5] MHW is the average of all high-water heights observed over a period of several years.

Figure 2 illustrates the continuous steel through-truss, spans, and four dolphins protecting the piers supporting the bridge's continuous through-truss spans.

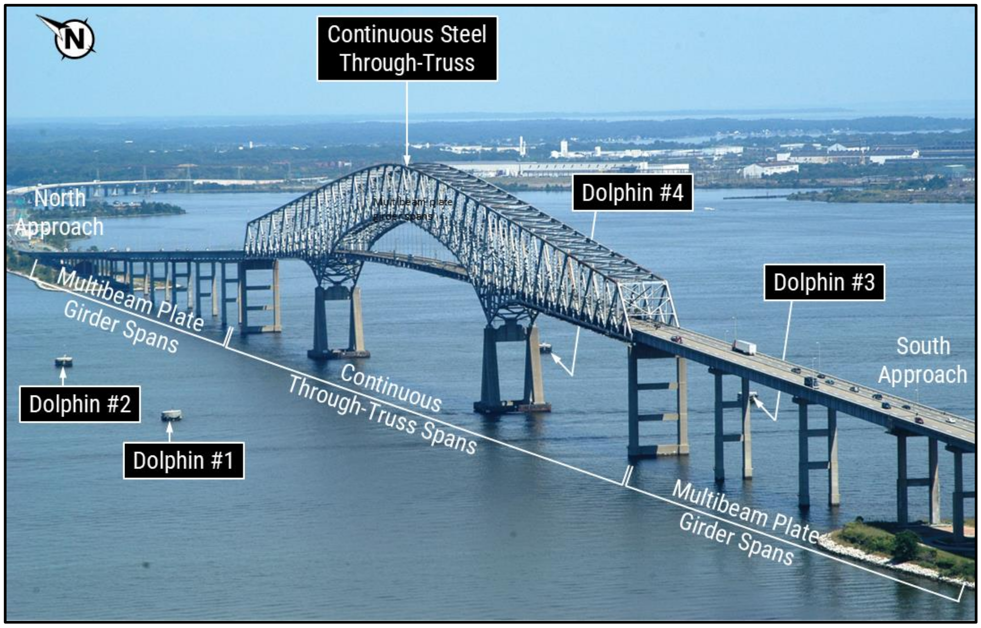

Figure 2. Key Bridge (source: MDTA revised).

2.1 Substructure

The substructure of a bridge supports the superstructure and transfers loads from it to the foundation; main components are abutments, piers, footings, and pilings. The substructure of the Key Bridge consisted of two reinforced concrete abutments[6] at each end of the bridge and 36 vertical piers (31 two-column rigid frame reinforced concrete piers, two rigid frame reinforced concrete piers, and three solid wall piers).

Figure 3 depicts the south and north abutments of the Key Bridge in photographs contained in the MDTA 2023 Main BIN Biennial Inspection Report.

Figure 3. South and north abutments of the Key Bridge (source: MDTA)

[6] A bridge abutment is a structure at the ends of a bridge that supports the bridge and transfers its weight to the ground.

Figure 4 depicts Pier 18, a rigid frame reinforced concrete pier, and Pier 19, a two-column reinforced concrete pier at the Key Bridge in photographs contained in the MDTA 2023 Main BIN Biennial Inspection Report.

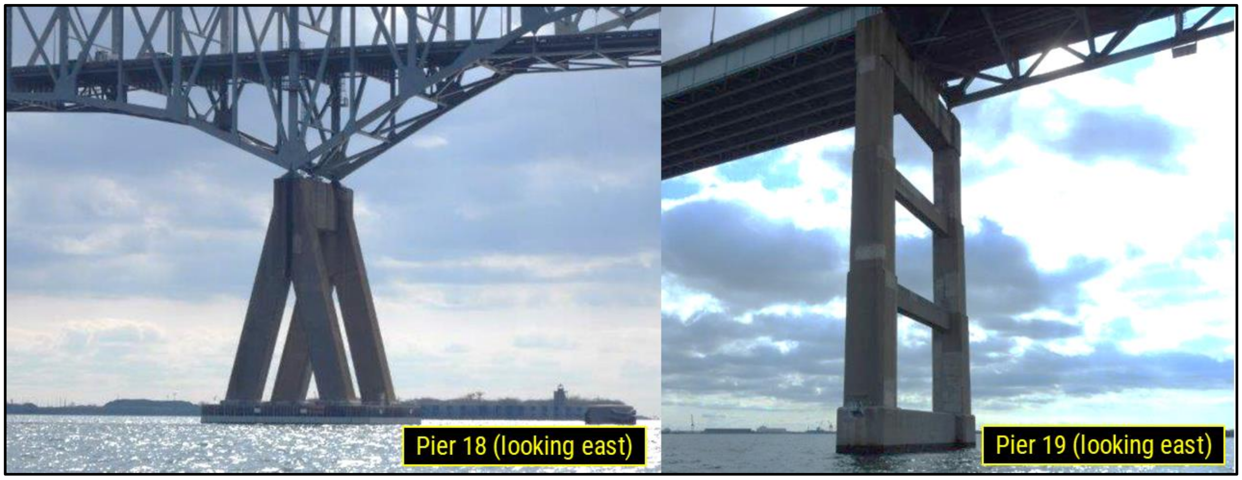

Figure 4. Rigid frame reinforced concrete pier (left) and two-column pier (right) (source: MDTA)

2.2 Superstructure

The superstructure of a bridge receives loads from the deck, such as traffic or pedestrian loads, and, in turn, transfers those loads to the substructure. The superstructure of the bridge consisted of seven continuous painted steel girders[7] that ran longitudinally along the length of the bridge and supported the bridge between the vertical piers (see **Figure 5**).

The superstructure also included 34 bridge spans between the vertical piers with the support of the girders and three truss spans not supported by girders. There were 25 shorter/shallower spans over land, nine longer/deeper multibeam plate girder spans over water, and three continuous steel through truss spans that crossed the primary navigation channel of the Patapsco River (see **Figure 6**). Each span was covered with a deck, the surface that vehicles drive on, which consisted of reinforced concrete with stay-in-place forms[8] in all spans.

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[7] A horizontal structural member supporting vertical loads. Larger girders are typically made of multiple metal plates that are welded or riveted together.

[8] Corrugated metal pans that span between girders or stringers, which support the wet concrete as it's placed for the deck and are not removed after the concrete has cured.

Figure 5 depicts the seven continuous painted steel girders at the Key Bridge near the south approach in a photograph (looking north from Pier 2) contained in the MDTA 2023 Main BIN Biennial Inspection Report.

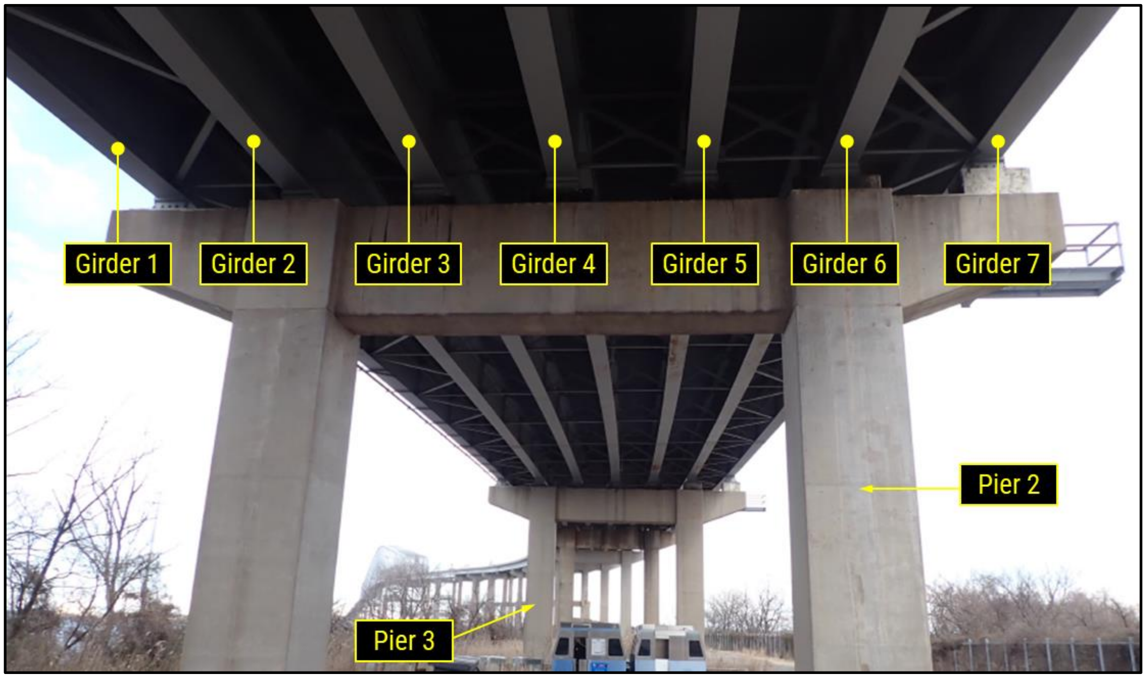

Figure 5. Continuous painted steel girders (source: MDTA).

Figure 6 depicts the types of spans at the Key Bridge in a photograph (looking north from south of the bridge) contained in the MDTA 2023 Main BIN Biennial Inspection Report.

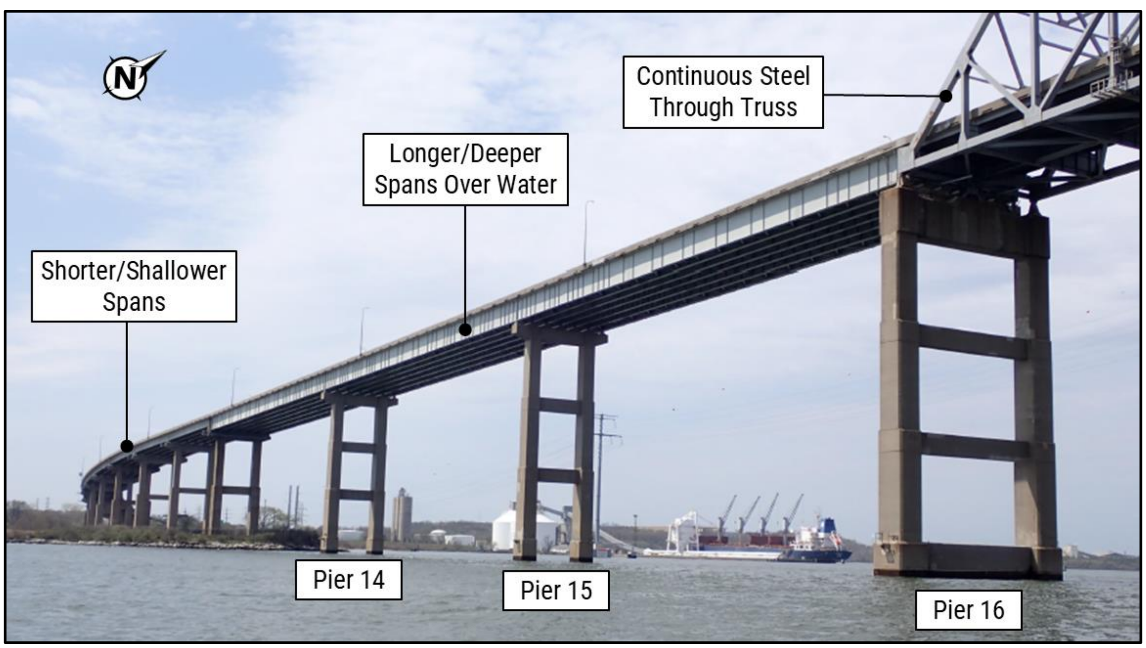

Figure 6. Three types of spans at the Key Bridge (source: MDTA).

2.3 Physical Protection Systems

Physical protection systems are protective structures provided on a bridge to fully or partially absorb the design vessel impact loads.[9] The Key Bridge was originally designed with physical protection systems at Pier 17 and Pier 18. The protection systems, which were in place when the bridge opened in 1977, included four dolphin structures with rubber fenders independent of the piers and fender systems mounted near the base of the piers. Prior to 1991 and the first edition of the AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges, there was no national-level guidance on the design of bridges for vessel collision or the design of pier protection against vessel collision. The 1969 Standard Specifications for Highway Bridges, Tenth Edition, to which the Key Bridge was designed, makes no mention of vessel collision. The dolphins at the Key Bridge (which were constructed with the bridge) were designed to project-specific design criteria. According to MDTA, the dolphins have not been redesigned since installation in 1977.

Figure 7 depicts Dolphin #1 and the fender system at Pier 17, the physical protection systems protecting Pier 17 for outbound vessels transiting the Key Bridge.

Figure 7. Pier 17 protection from outbound vessels transiting the Key Bridge (source: MDTA revised).

[9] See *Section 7.3 of Physical Protection Systems* in AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges. 2nd Edition. Washington, DC: page 96.

2.3.1 Dolphins

When the Key Bridge was constructed, four dolphins were also constructed at the same time to protect Pier 17 and Pier 18 and were aligned with the extents of the channel. Large-diameter dolphins have frequently been used in the U.S. and Canada for protection of bridge piers.[10] The circular shape of the dolphins can help deflect aberrant vessels away from a pier.[11] If the dolphin is stronger than the vessel, then the vessel will absorb most of the impact energy, and if the dolphin is weaker than the vessel, then the dolphin absorbs most of the energy by large translational (sliding) and rotational deformations.[12] The centers of Dolphin #1 and Dolphin #2 were located 489 feet west of the centers of Pier 17 and Pier 18.[13] The centers of Dolphin #3 and Dolphin #4 were located 364 feet east of the centers of Pier 17 and Pier 18. All the dolphins were approximately 550 feet clear of the centerline of the navigation channel.

Figure 8 illustrates the locations of the four dolphins that protected Pier 17 and Pier 18.

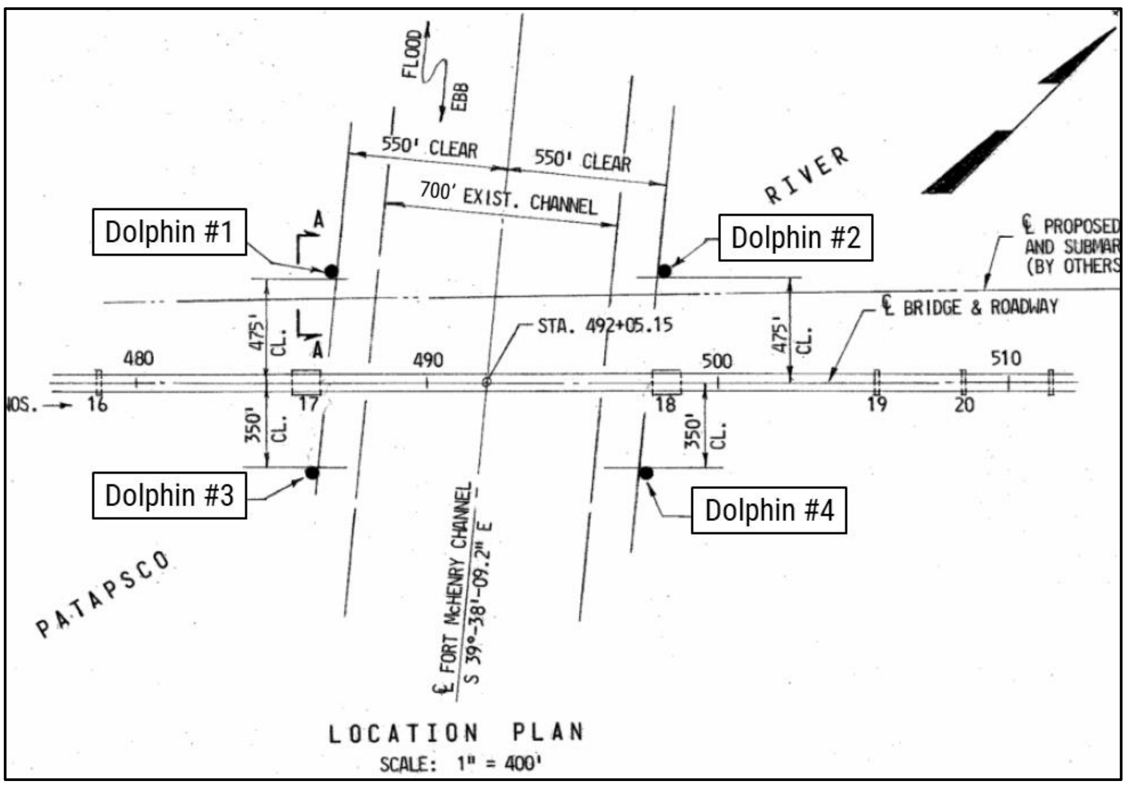

Figure 8. Locations of the dolphins (source: MDTA revised).

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[10] See *Section C7.3.3 Dolphin Protection* in AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges. 2nd Edition. Washington, DC: page 114.

[11] Ibid.

[12] Ibid.

[13] The measurements of 475 and 350 feet depicted in Figure 8 were from the center of the pier to the circumference of the 28-foot-diameter dolphins; therefore, the distance to the center of the dolphins was equivalent to the measurement shown in the figure plus half the diameter of the dolphin (14 feet).

Each dolphin was composed of 25.46-foot-diameter driven steel sheet pile ring filled with tremie concrete[14] and a 28-foot-diameter reinforced concrete cap (see **Figure 9** and **Figure 10**). Attached at various locations on each dolphin were 17-foot-long preformed rubber fenders.

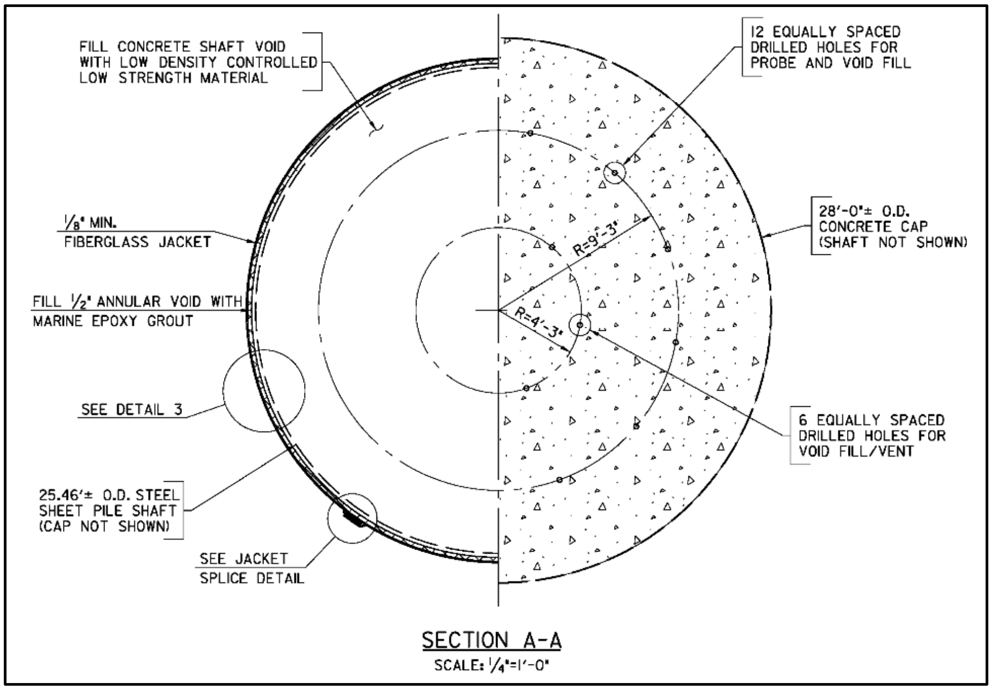

Figure 9: Typical plan view of the dolphin (source: MDTA).

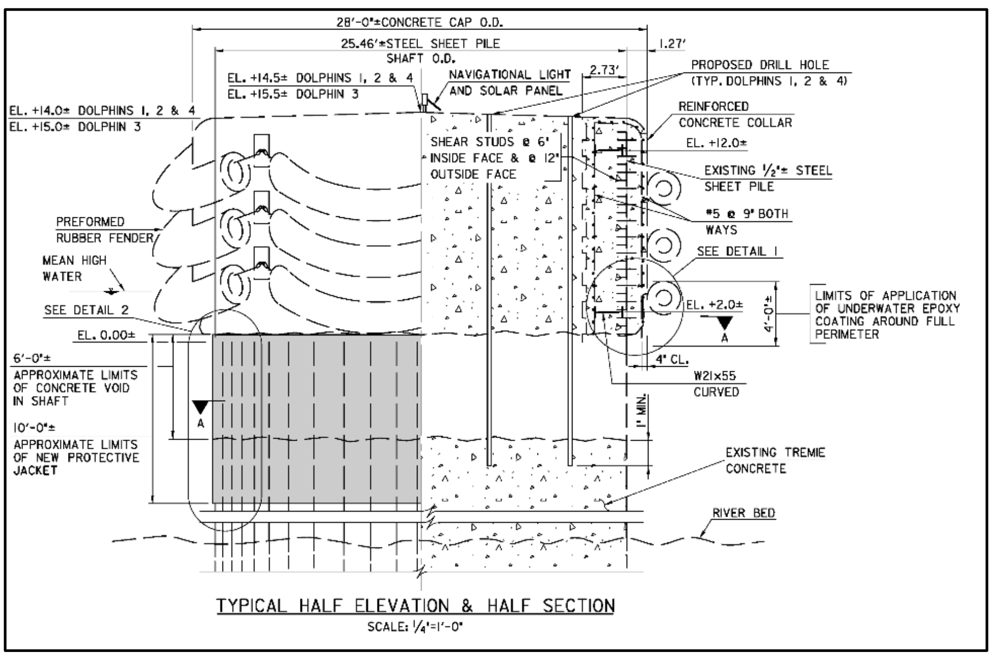

Figure 10: Typical half elevation/section view of the dolphin (source: MDTA).

[14] Tremie concrete refers to placement by gravity feed from a hopper through a vertical pipe extending from above the surface to the underwater floor.

Timber or rubber fenders are usually placed on the outer perimeter of the dolphin to act as an anti-sparking surface to prevent metal-to-metal contact in the event of collision with a steel-hulled vessel carrying flammable products.[15] None of the four dolphins were contacted by the *Dali* during the collision.

2.3.2 Fender System

Crushable concrete box and timber fender systems surrounded Pier 17 and Pier 18 (see **Figure 11** and **Figure 12**). The crushable concrete fender system was composed of hollow, thin-walled, concrete box structures attached to the pier. The timber fender was attached to the outer face of the concrete box fender. Timber fenders are frequently used for bridge protection because of their relatively low cost and good energy absorption characteristics; however, for the relatively large collision impact loads associated with design vessels in the Guide Specifications, the resulting timber fenders would have to be extremely large and might be uneconomical in most circumstances.[16]

Figure 11. Photograph taken in 2021 looking north at Pier 17 (Pier 18 was similar) (source: MDTA).

Figure 12. Photograph taken in 2021 looking inside of Pier 17 (Pier 18 was similar) (source: MDTA).

The timber fender surrounding Pier 17 was composed of vertical (6-by-12-inch, 12-by-12-inch, and 14-by-16-inch) and horizontal (12-by-12-inch) timber members in a grillage geometry attached to the face of the concrete box fender. There were also steel plates secured to the vertical timber, near the base of the fender.

[15] Ibid.
[16] See *Section C7.3.1.1 Timber Fenders* in AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges. 2nd Edition. Washington, DC: page 97.

Figure 13 and **Figure 14** illustrate the plan and section views of the fendering system at Pier 17 and Pier 18.

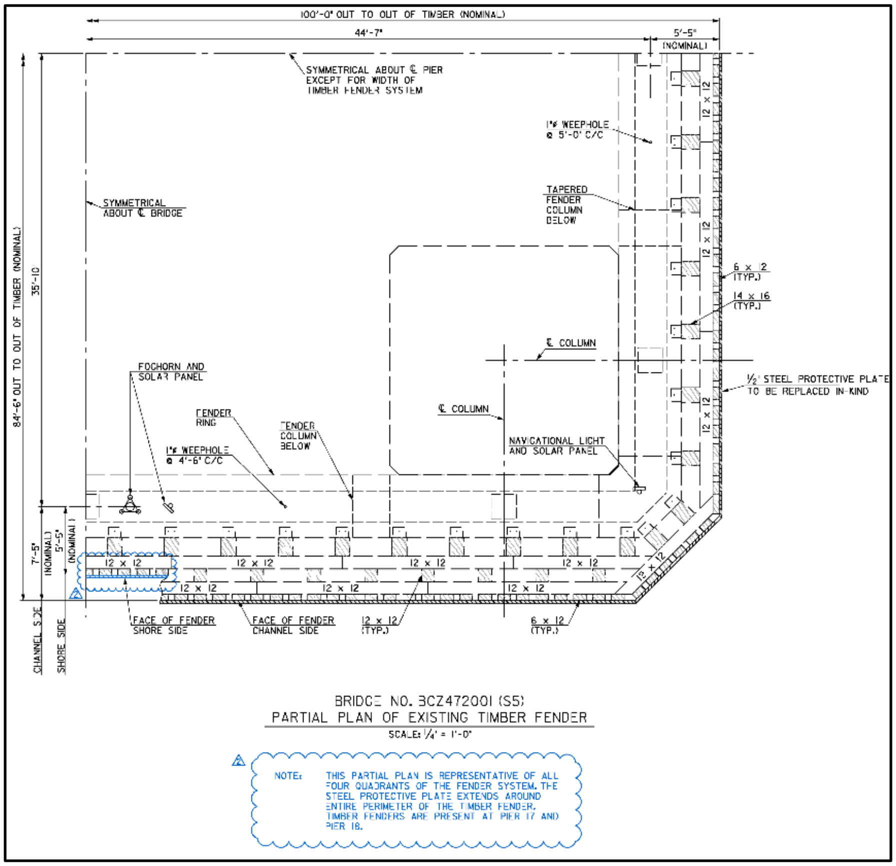

Figure 13. Partial plan view of fender system at Pier 17 and Pier 18 (source: MDTA).

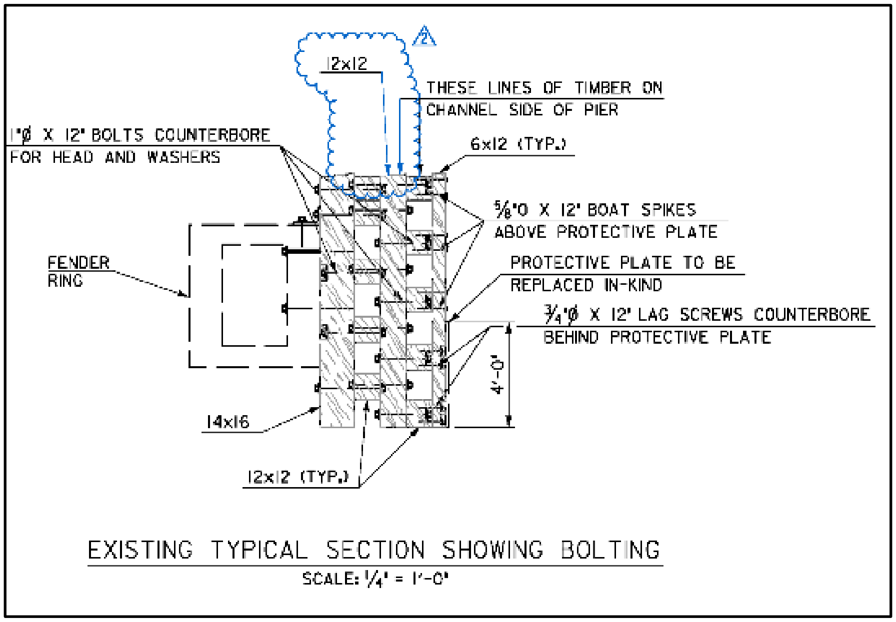

Figure 14. Typical section view of the fender system at Pier 17 and Pier 18 (source: MDTA)

Both fender systems surrounding piers 17 and 18 were damaged during the collision and subsequent collapse of the bridge. The most significant damage to Pier 17 occurred on the opposing side of the channel, while the fender on the channel side remained largely intact (see **Figure 15)**. The most significant damage to Pier 18 occurred on the channel side where portions of the fender were no longer present (see **Figure 16)**. Components of the truss spans came to rest in the areas of the damaged and missing fender sections.

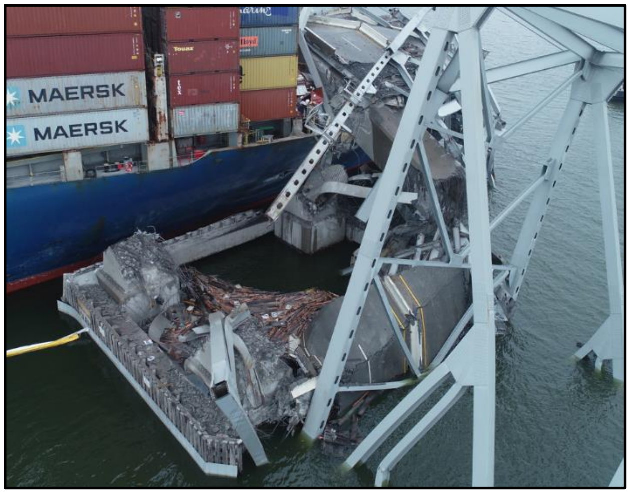

Figure 15. Post-collapse condition of the fender surrounding Pier 17.

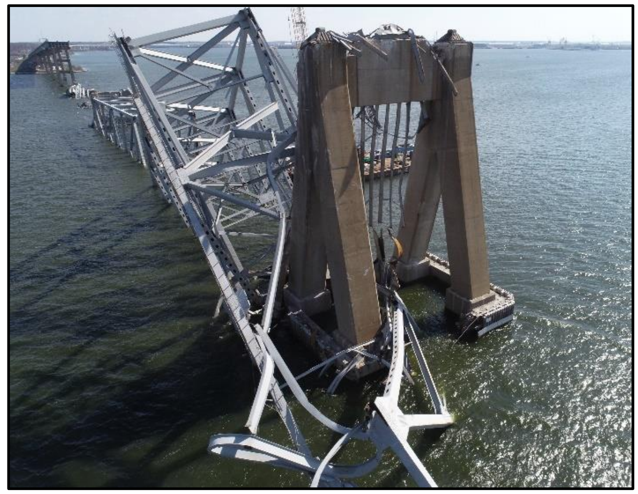

Figure 16. Post-collapse condition of the fender surrounding Pier 18.

2.3.3 Bridge Owner's Responsibility for Bridge Pier Protection

The 2020 AASHTO *LRFD Bridge Design Specifications*, 9th Edition, indicated the following regarding the bridge owner's responsibility for bridge pier protection.[17]

> "***3.14.2 – Owner's Responsibility***
>
> *The Owner shall establish and/or approve the bridge classification, the vessel traffic density in the waterway, and the design velocity of vessels for the bridge. The Owner shall specify or approve the degree of damage that the bridge components, including protective systems, are allowed to sustain."*[18]

(*This space intentionally left blank*)

[17] See Section 3.14.2 - *Owner's Responsibility* in AASHTO *LRFD Bridge Design Specifications*, 9th Edition, page 3-162.

[18] The requirements enumerated in the LRFD only apply to the design and construction of bridge projects. They are not standing requirements for bridge owners and their existing bridges.

3.0 Horizontal and Vertical Alignments

Horizontal and vertical alignments for the Key Bridge were established based upon project plans obtained from MDTA.[19] From south to north, the horizontal alignment of the bridge began with an approximate 128-foot-long tangent on a bearing of N 69°00′00″ E. The horizontal alignment continued with an approximate 1,608-foot-long, right-to-left horizontal curve with a radius of approximately 3,820 feet. At the end of the horizontal curve was a second tangent that was approximately 6,599 feet on a bearing of N 44°53′00″ E. The horizontal alignment ended with an approximate 751-foot-long, left-to-right horizontal curve with a radius of approximately 11,459 feet.[20]

From south to north, the vertical alignment of the bridge began approximately 46 feet before the end of a 1,000-foot-long sag vertical curve. The alignment continued from an elevation of approximately 52 feet at a profile grade of positive 4.0 percent for approximately 3,273 feet before a 1,700-foot-long crest vertical curve began at an elevation of 183 feet. The high point of the vertical curve was at an elevation of approximately 200 feet and was located at the middle of the center span. The vertical curve ended at an elevation of approximately 183 feet. A negative 4.0 percent grade continued for approximately 4,068 feet to the north bridge abutment.[21]

4.0 South Approach Spans

The following description of the South Approach Spans was derived from the MDTA 2023 Main BIN Biennial Inspection Report.[22] The South Approach Spans, which had an overall length of approximately 2,847 feet between the center-to-center bearings of the South Abutment and Pier 16, consisted of seven continuous painted steel girders, with 13 shorter/shallower spans over land (Span 1 through Span 13) and three longer/deeper spans over water (Span 14 through Span 16). The span arrangement consisted of one four-span unit (Span 1 through Span 4) and four three-span units (Span 5 through Span 7, Span 8 through Span 10, Span 11 through Span 13, and Span 14 through Span 16). The deck consisted of reinforced concrete with stay-in-place forms in all spans.

[19] See Bridge Protection Systems Attachment – Baltimore Harbor Outer Crossings Patapsco River Bridge As-Built Plans.
[20] See Bridge Protection Systems Attachment: NTSB Horizontal and Vertical Alignments.
[21] Ibid.
[22] See Bridge Protection Systems Attachment – MDTA 2023 Main BIN Biennial Inspection Report.

The substructure consisted of 16 two-column reinforced concrete piers and one reinforced concrete abutment. All piers had solid concrete caps with 0 to 2 intermediate concrete struts depending on the height of the pier. These piers in the river were not equipped with fendering systems.

Figure 17 depicts plan and elevation views of the South Approach Spans of the bridge.

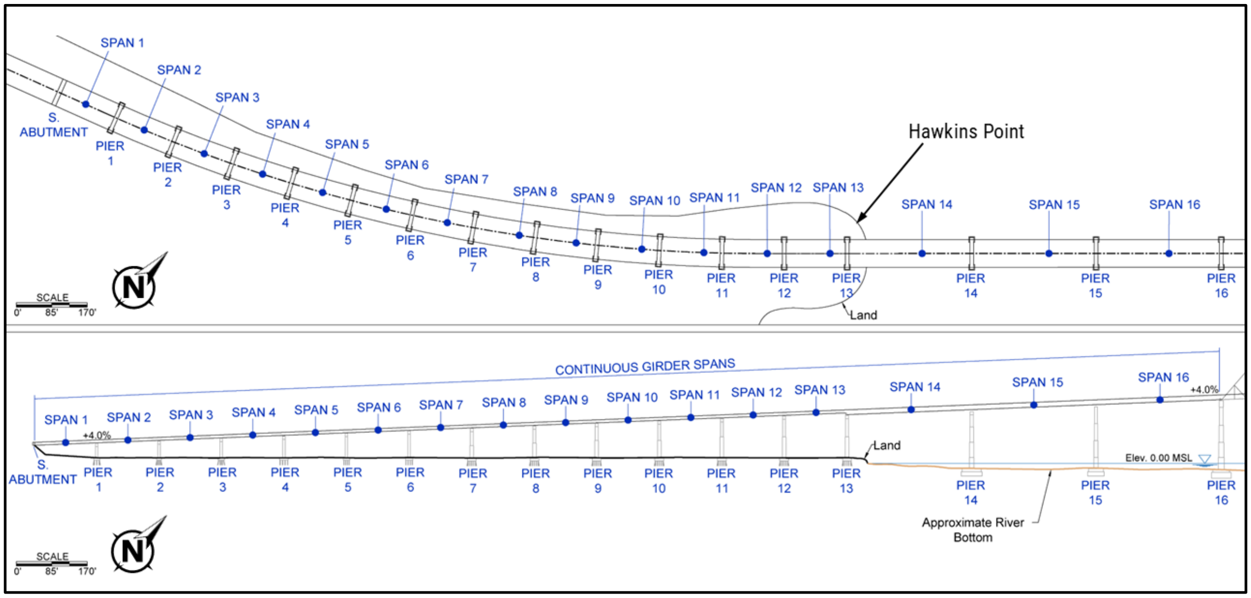

Figure 17: Plan (top) and elevation (bottom) views of the South Approach Spans of the Key Bridge.

5.0 Main Spans

The following description of the Main Spans was derived from the MDTA 2023 Main BIN Biennial Inspection Report.[23] The Main Spans, which had an overall length of approximately 2,643 feet between the center-to-center bearings of Pier 16 and Pier 19, consisted of three continuous steel through truss spans that crossed the primary navigation channel of the Patapsco River. The two side spans (Span 17 and Span 19) were approximately 722 feet in length. The main span (Span 18), a suspended deck truss span[24] that was over the navigation channel, was 1,200 feet in length. The deck consisted of reinforced concrete with stay-in-place forms present in all spans.

The substructure consisted of two rigid frame reinforced concrete piers (Pier 17 and Pier 18) and two two-column reinforced concrete piers (Pier 16 and Pier 19). Pier 16 and Pier 19 had concrete caps with two intermediate concrete struts. There were fender systems at main span Piers 17 and 18.

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[23] Ibid.

[24] For 1,020 feet of this span, the deck was suspended from the underside of the truss on 2 7/8" diameter galvanized cables.

Figure 18 depicts plan and elevation views of the Main Spans of the bridge.

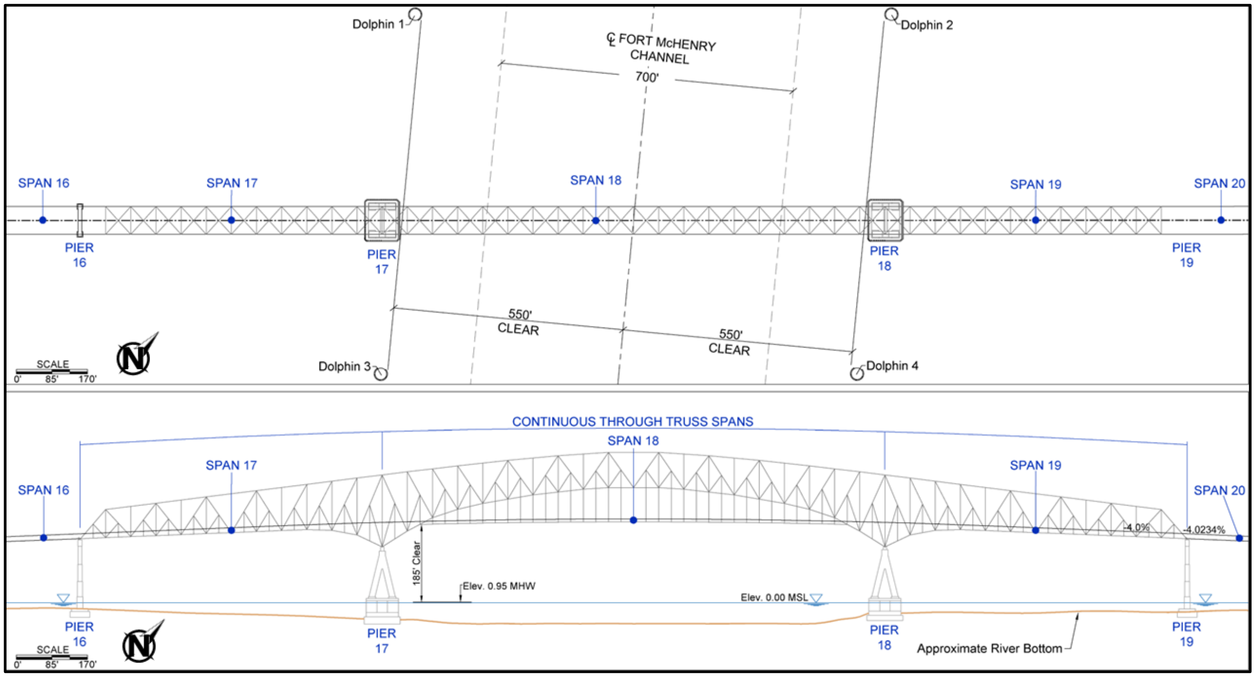

Figure 18: Plan (top) and elevation (bottom) views of the Main Spans of the Key Bridge.

6.0 North Approach Spans

The following description of the North Approach Spans was derived from the MDTA 2023 Main BIN Biennial Inspection Report.[25] The North Approach Spans, which had an overall length of approximately 3,596 feet between the center-to-center bearings of Pier 19 and the North Abutment, consisted of seven continuous painted steel girders, with 12 shorter/shallower spans over land (Span 26 through Span 37) and six longer/deeper spans over water (Span 20 through Span 25). The span arrangement consisted of six three-span units (Span 20 through Span 22, Span 23 through Span 25, Span 26 through Span 28, Span 29 through Span 31, Span 32 through Span 34, and Span 33 through Span 37). The deck consisted of reinforced concrete with stay-in-place forms in all spans.

The substructure consisted of 15 two-column reinforced concrete piers, three solid wall piers, and one reinforced concrete abutment. All two-column piers had solid concrete caps with 0 to 2 intermediate concrete struts depending on the height of the pier. None of the piers supporting the North Approach Spans were equipped with fender systems.

[25] Ibid.

Figure 19 depicts plan and elevation views of the End (North) Approach Spans of the bridge. It should be noted that Pier 33 through Pier 36 and Span 34 through Span 37 are not shown.

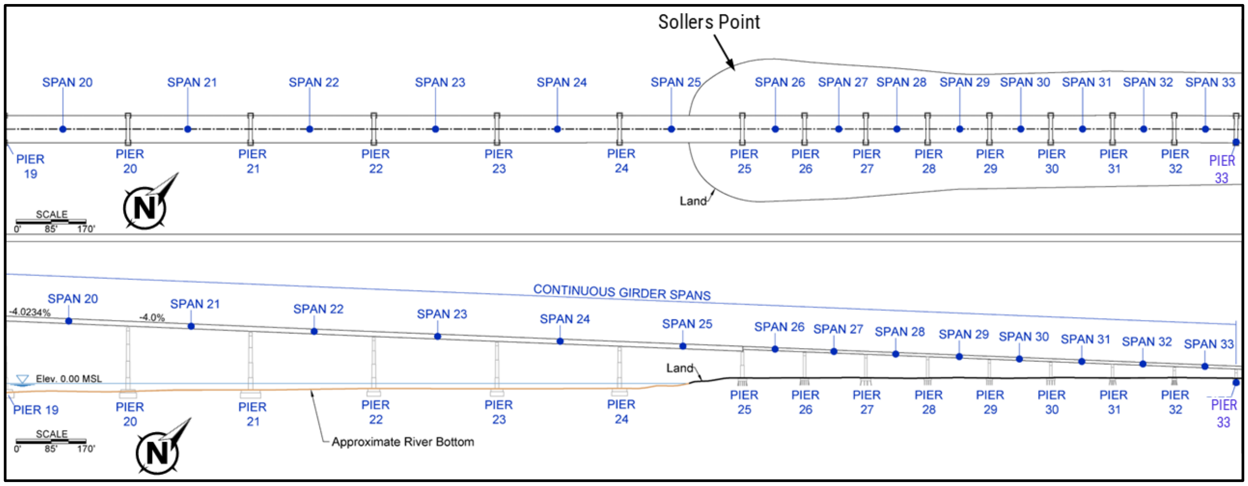

Figure 19: Plan (top) and elevation (bottom) views of the End Approach Spans of the Key Bridge.

7.0 Description of Bridge Collapse

As a result of the impact to Pier 17 by the starboard bow of the *Dali*, Pier 17 failed and collapsed, resulting in the collapse of the Main Spans (Span 17, Span 18, and Span 19), Span 20, Span 21, and Span 22. Pier 19 collapsed down to the lower intermediate strut. A strut is a structural component connecting two columns that can be horizontal, vertical, or inclined, and can resist both axial and lateral loads. Both intermediate struts on Pier 20 and Pier 21 were destroyed and the piers were collapsed down to the approximate level of the water. The strut on Pier 18 sustained contact damage from the collapsing superstructure. The fender systems on Pier 17 and Pier 18 were also significantly damaged due to the collapsing superstructure.[26]

8.0 Bridge Inspections and Condition

The Key Bridge was subject to regular inspections through the MDTA's inspection program, in accordance with the National Bridge Inspection Standards (NBIS).[27] These periodic inspections are intended to maintain safe bridge operation and prevent structural and functional failures. In addition to routine bridge inspections, the bridge's steel-truss design and location over the Patapsco River required two additional types of inspections. One of these additional inspections focused on the nonredundant steel tension members within the steel truss and the other examined the bridge's underwater members. The last inspection of the

[26] See Bridge Protection Systems Attachment: FSK Bridge Post-Collapse Damage.
[27] 23 CFR 650 Subpart C

nonredundant steel tension members was completed in May 2023,[28] and the last underwater bridge inspection was completed in March 2021.[29]

Data from all three inspections were entered into the FHWA National Bridge Inventory which records bridge inventory and condition data collected from states, federal agencies, and tribal governments. The 2024 Structure Inventory and Appraisal (SIA) form indicated the following: a) the conditions of the deck, the superstructure, and the substructure of the Key Bridge as a Code 6, indicating a satisfactory condition (see **Figure 20,** left) and b) the pier protection was rated as a Code 2, indicating the pier protection is in place and functioning (see **Figure 20,** right).

Code	Description
N	NOT APPLICABLE
9	EXCELLENT CONDITION
8	VERY GOOD CONDITION - no problems noted.
7	GOOD CONDITION - some minor problems.
6	SATISFACTORY CONDITION - structural elements show some minor deterioration.
5	FAIR CONDITION - all primary structural elements are sound but may have minor section loss, cracking, spalling or scour.
4	POOR CONDITION - advanced section loss, deterioration, spalling or scour.
3	SERIOUS CONDITION - loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	CRITICAL CONDITION - advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.
1	"IMMINENT" FAILURE CONDITION - major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.
0	FAILED CONDITION - out of service - beyond corrective action.

Code	Description
1	Navigation protection not required
2	In place and functioning
3	In place but in a deteriorated condition
4	In place but reevaluation of design suggested
5	None present but reevaluation suggested

Figure 20. Codes and descriptions for the conditions of the deck, superstructure, substructure, and pier protection (source: FHWA Recording and Coding Guide for the SIA of the Nation's Bridges).

8.1 Nonredundant Steel Tension Member Plan

The bridge was designed with nonredundant steel tension members (NSTMs) and the plan identifies these members so that inspectors can ensure those members are documented and inspected appropriately.[30] A bridge requires nonredundant steel member inspection if it contains one or more non-load path redundant steel tension members, components, or connections. An NSTM meets the following three criteria: 1) it is made of steel, 2) it is fully or partially in tension, and 3) failure of the component would likely cause the bridge to partially or fully collapse. In 2022, the FHWA started using the term nonredundant steel tension member, replacing the previous term, fracture critical member. NSTMs must be inspected at arms-length every 24 months or less in accordance with the NSTM inspection criteria and procedures.[31]

[28] See Bridge Protection Systems Attachment – MDTA 2023 Bridge Inspection Report (S17-S19).
[29] See Bridge Protection Systems Attachment – MDTA 2021 Underwater Inspection Report.
[30] See Bridge Protection Systems Attachment – NTSB-Generated Nonredundant Steel Tension Member Plan.
[31] eCFR: 23 CFR 650.305 – Definitions, "Hands-on inspection".

F. VIDEO REVIEW

1.0 Introduction

NTSB Investigators reviewed two videos that recorded the approach of the *Dali*, collision with Pier 17, and subsequent collapse of the bridge. The videos were recorded by security cameras maintained by the Maryland Natural Resources Police (NRP) and MDTA. The field of view of the MDTA video did not record the collapse of bridge elements north of Pier 18.

Figure 21 depicts the location of each security camera and **Figure 22** depicts their approximate fields of view.

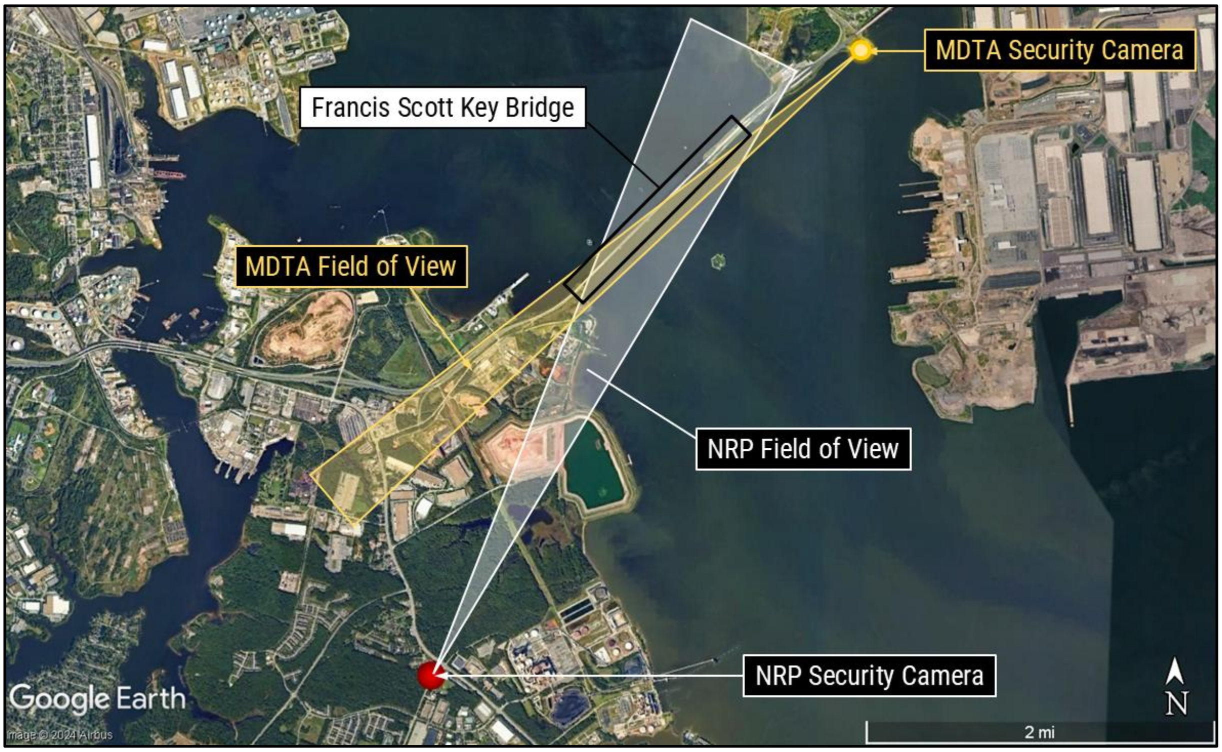

Figure 21. Aerial view showing locations of the security cameras and the approximate fields of view of each video (source: Google Earth revised).

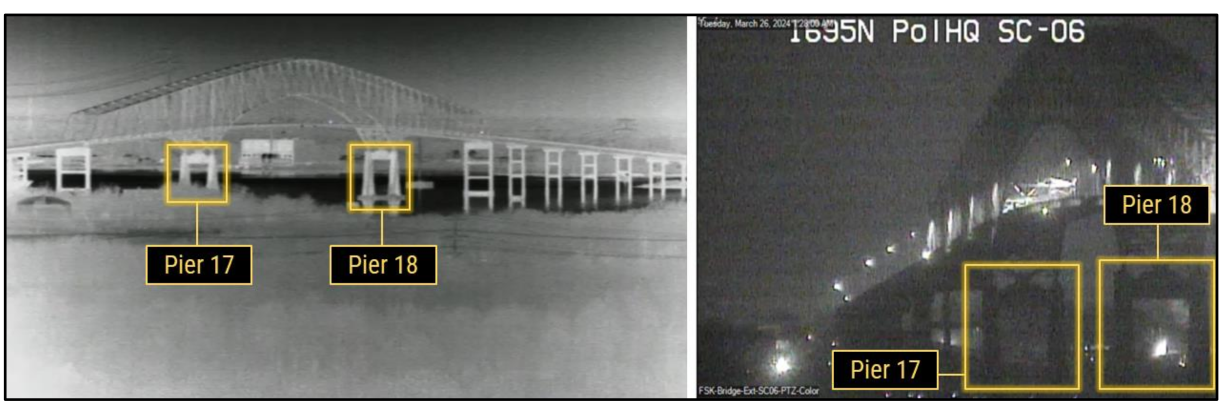

Figure 22. Fields of view of the security cameras, NRP (left) and MDTA (right).

1.1 Maryland Natural Resources Police Video

The NRP security camera that recorded the obtained video was located on a radio tower near the corner of Steele Ridge Drive and Solley Road. The camera was a Forward Looking InfraRed (FLIR) camera manufactured by Teledyne FLIR Systems. Video, which was recorded at 20 frames per second (fps), was recorded to a network digital video recorder (DVR) located at the Maryland NRP Communications center. There was no timestamp on the video. To synchronize the two videos specific impacts were identified and utilized. The MDTA video, which had a timestamp, was utilized for timing.

1.2 Maryland Transportation Authority Video

The MDTA security camera was located at the MDTA Police Headquarters/Training Academy Complex [4330 Broening Highway], located near the north end of the Key Bridge. The camera was manufactured by FLIR Systems. Video, which was recorded at 7 frames per second (fps), was recorded to a network video recorder (NVR) located at the MDTA. There was a timestamp at the upper left corner of the video frame, which was based upon MDOT Network Time Protocol (NTP)[32] servers. Based upon data contained within the voyage data recorder (VDR) onboard the Dali, which recorded the sound of the bridge collapsing, the timestamp in the video was 55 seconds slower than the actual time. All references to time were based on the actual time determined from VDR data.

2.0 Sequence of Collapse

Using VLC Media Player, a frame-by-frame review of both videos was conducted to determine the sequence of the collapse. If applicable, time was based upon the timestamp depicted in the MDTA video, which was adjusted by adding 55 seconds.

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[32] NTP is a protocol that allows the synchronization of system clocks (from desktops to servers).

Figure 23 shows that at 1:29:09 AM, a heat signature was visible in the NRP video when the starboard bow of the *Dali* impacted the northwest column of Pier 17 approximately 20 feet above the waterline. A heat signature is the infrared energy emitted by an object. An infrared camera measures the emitted energy and displays warmer objects in white and cooler objects in black.

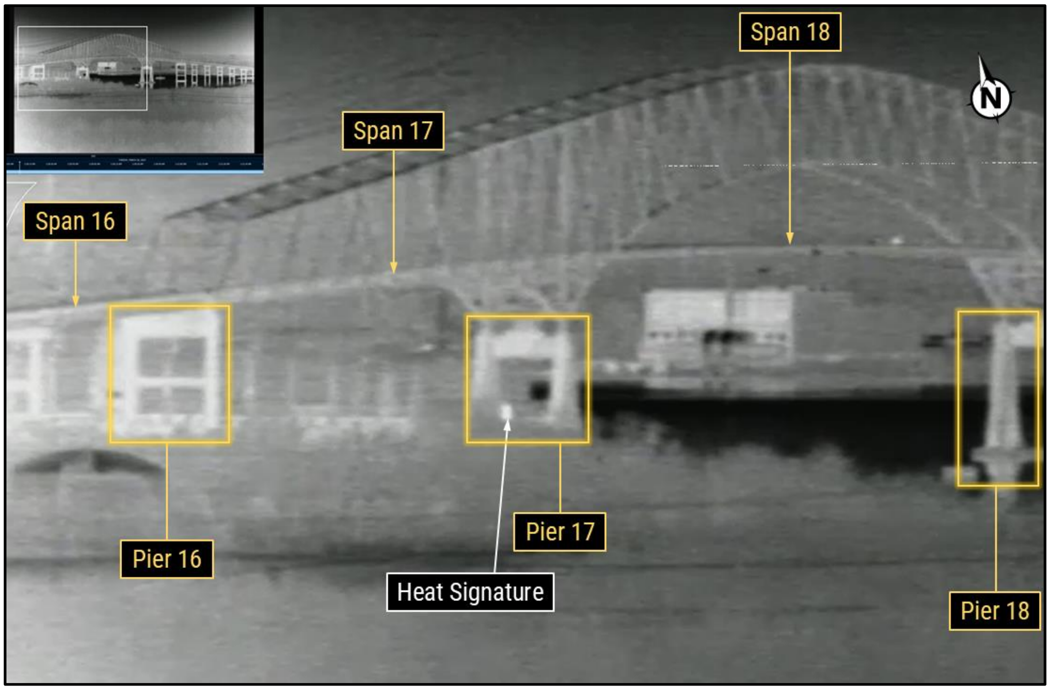

Figure 23. NRP video (zoomed in) depicting the initial impact to the northwest column of Pier 17.

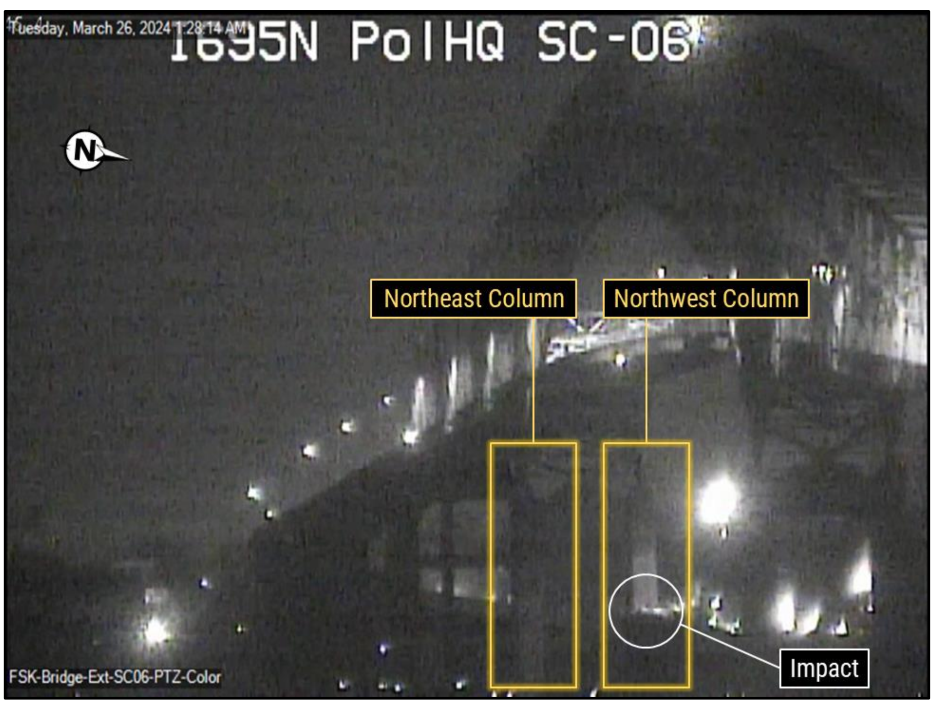

Figure 24. MDTA video depicting the initial impact to Pier 17.

Figure 25 shows that at 1:29:13 AM, a second heat signature, above the heat signature from the initial impact, and displacement of concrete were visible in the NRP video when the northwest column of Pier 17 was likely impacted by container(s) near the starboard bow of the *Dali*.

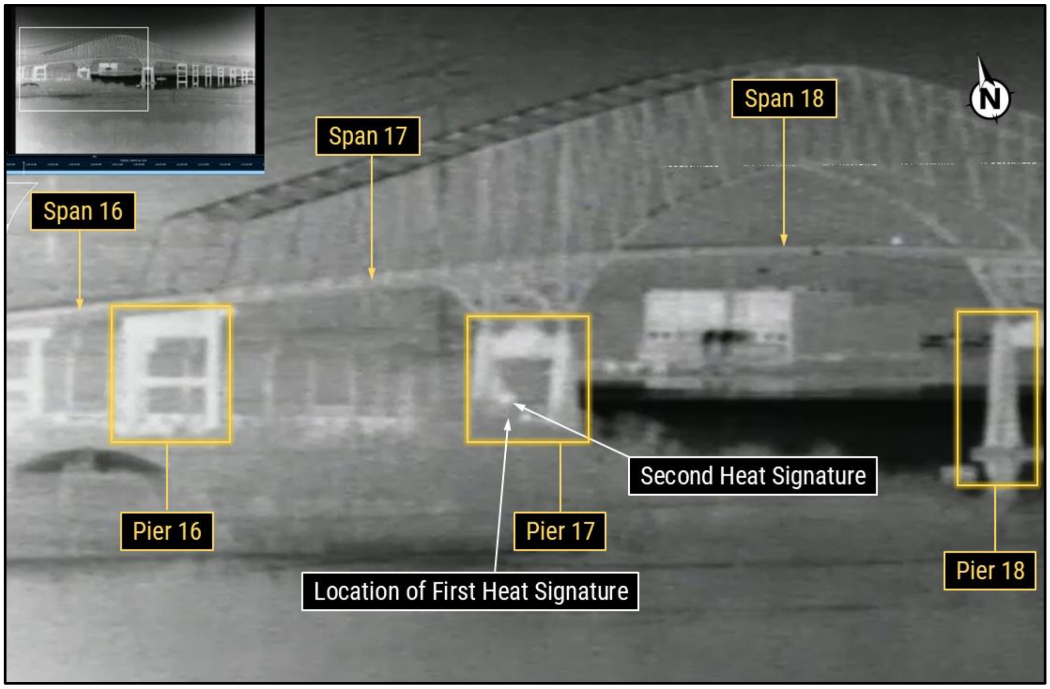

Figure 25. NRP video depicting a second impact to the northwest column of Pier 17.

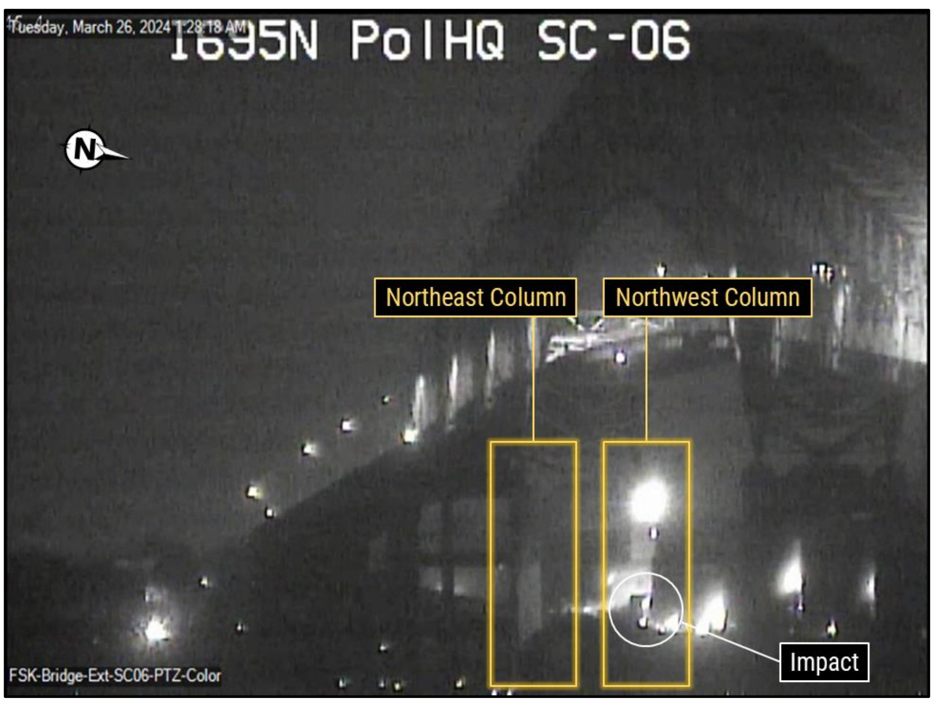

Figure 26. MDTA video depicting the second impact to the northwest column of Pier 17.

Figure 27 shows that at 1:29:16 AM, there was a heat signature near the northeast column of Pier 17, likely the result of impact(s) by container(s) near the starboard bow of the *Dali*. Displacement of water at the bow of the *Dali* was also observed likely the result of lateral displacement of the bow during impact.

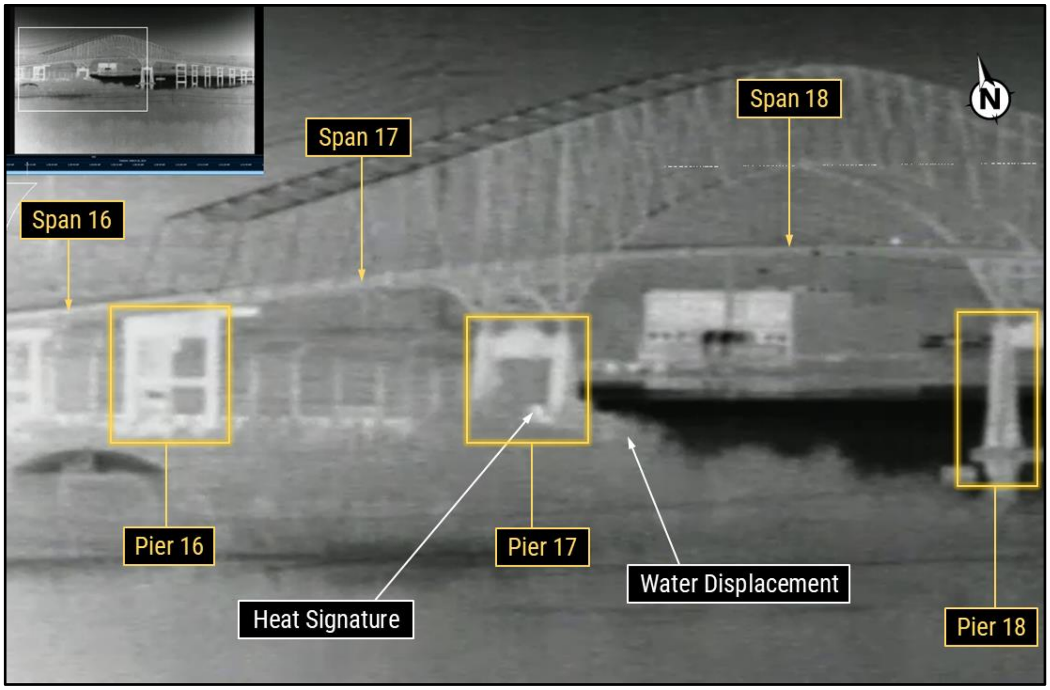

Figure 27. NRP video depicting the initial impact to the northeast column of Pier 17.

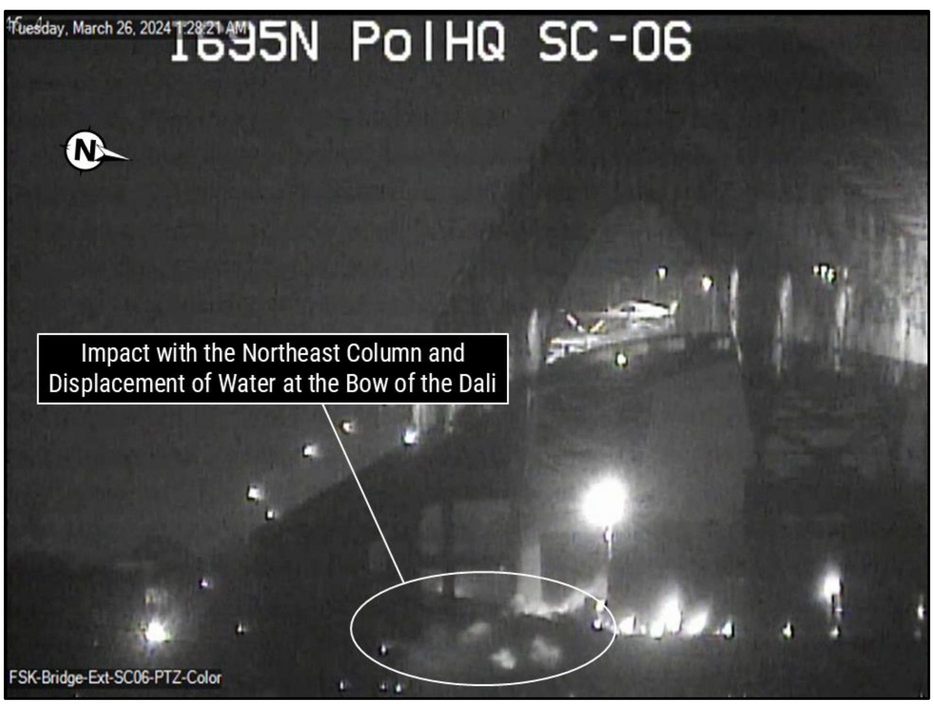

Figure 28. MDTA video depicting the initial impact to the northeast column of Pier 17.

Figure 29 shows that at 1:29:20 AM, heat signatures at both bearings of Pier 17 were visible in the NRP video after the northeast column failed and collapse of the bridge began.

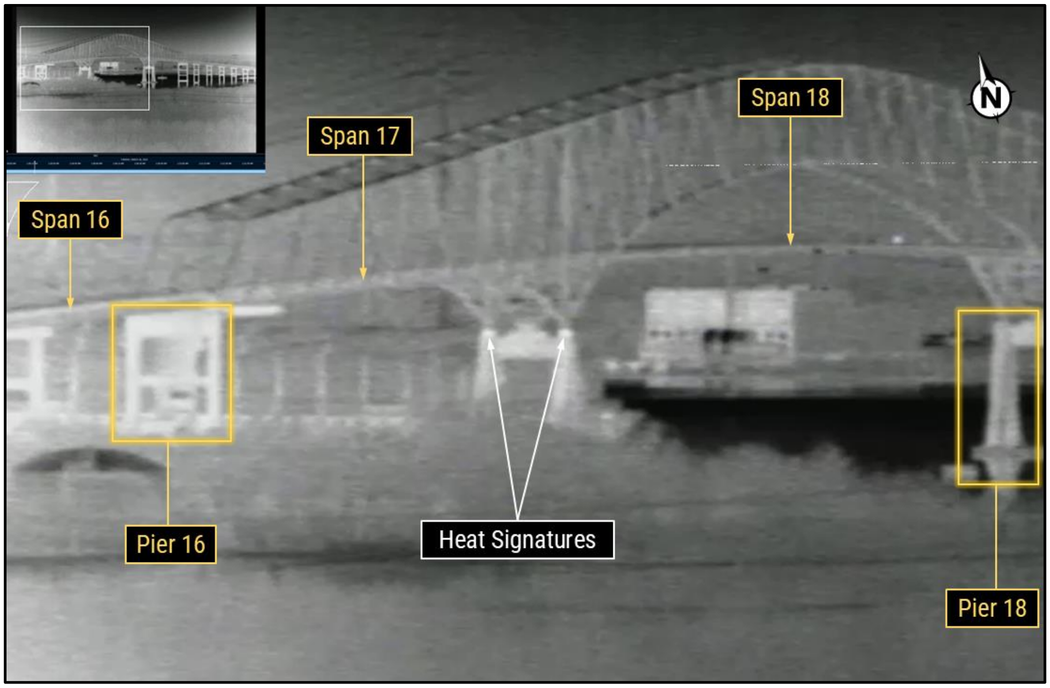

Figure 29. NRP video depicting heat signatures at both bearings of Pier 17.

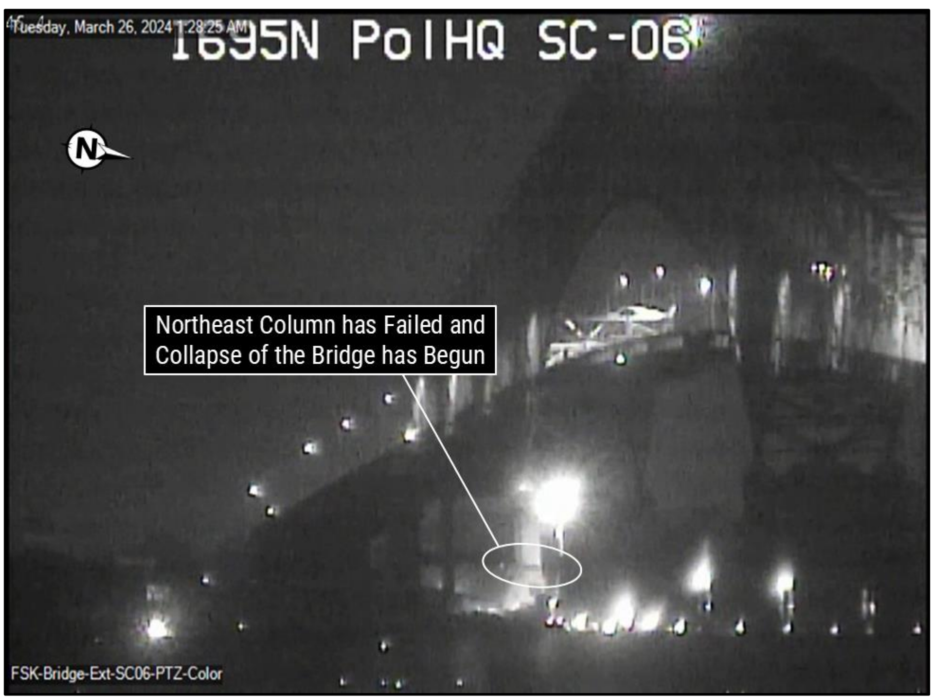

Figure 30. MDTA video depicting the collapse of the northeast column of Pier 17.

Figure 31 shows that at 1:29:22 AM, Pier 17 has collapsed [A], Span 17 [B] and Span 18 [C] have collapsed, the joints of the upper chord of the steel truss at Span 17 have failed [D], and the north end of the steel truss was displaced upward and off of Pier 19 [E].

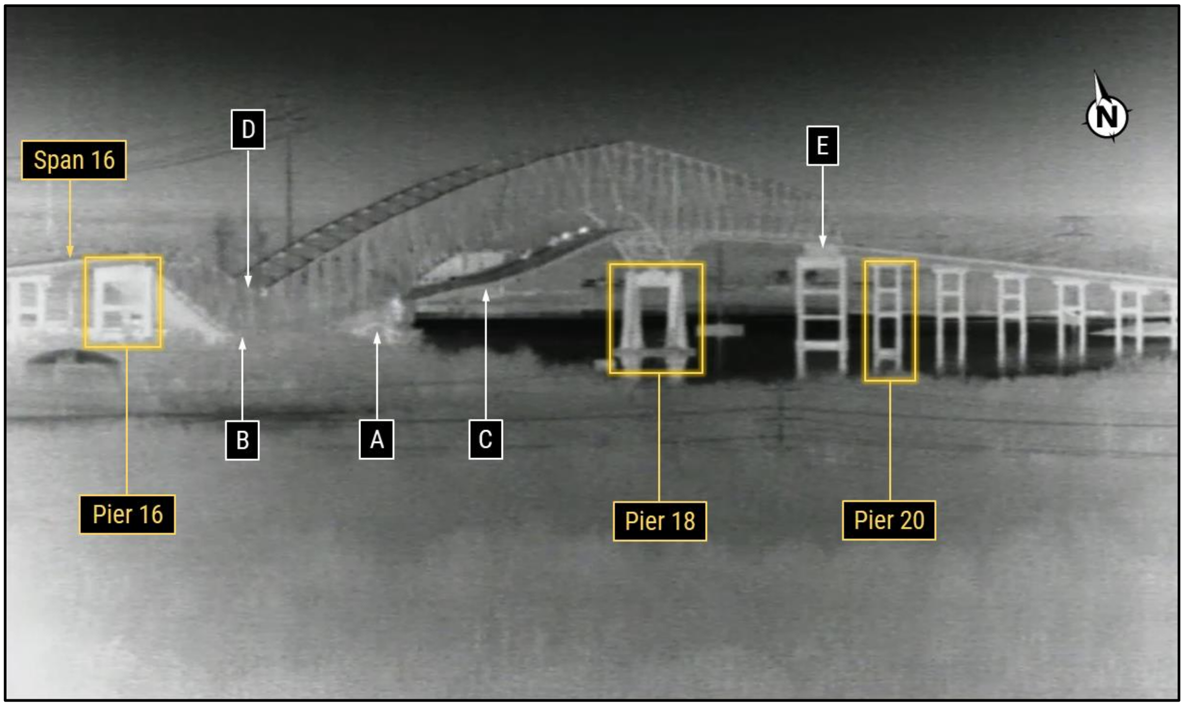

Figure 31. NRP video depicting the collapse of Pier 17, Span 17, Span 18, and upward displacement of Span 19 and the north end of the steel truss.

Figure 32. MDTA video depicting the second impact to the northwest column of Pier 17.

Figure 33 shows that at 1:29:23 AM, a heat signature at the west column of Pier 19 was visible when the north end of the steel truss moved downward from its elevated position and re-contacted the pier.

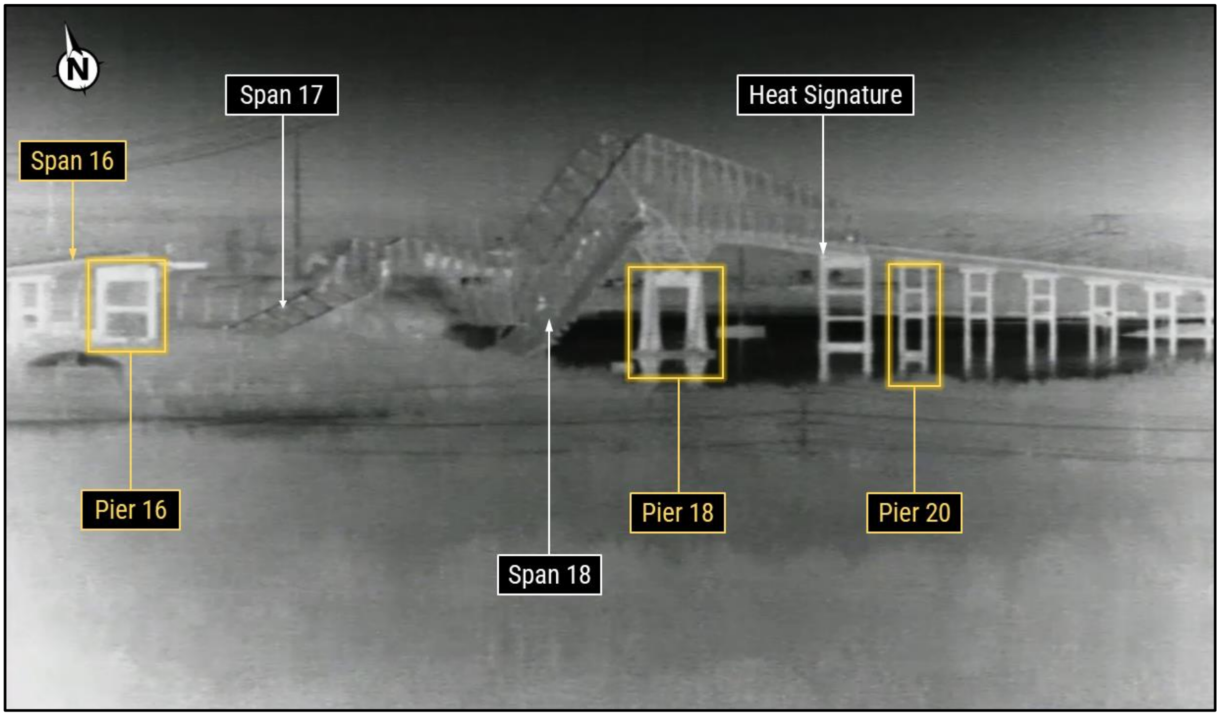

Figure 33. NRP video depicting a heat signature at the east column of Pier 19.

Figure 34. MDTA video depicting the collapse of Pier 17, Span 17, Span 18, and the steel truss.

Figure 35 depicts the upper chord of the truss of Span 18 has separated [A] and a heat signature was visible at the east column of Pier 19 as Span 19 contacted the pier as it collapsed [B].

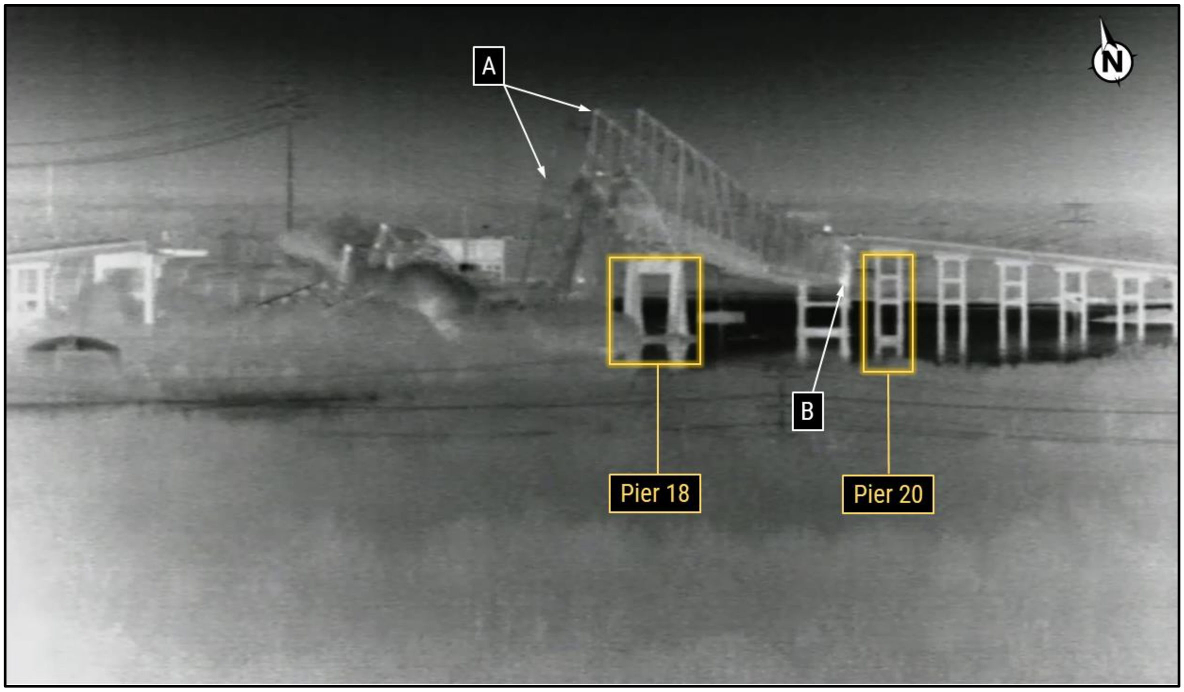

Figure 35. NRP video depicting the collapse of Span 19 and remaining steel truss.

Figure 36 shows the collapse of Span 19 and Span 20

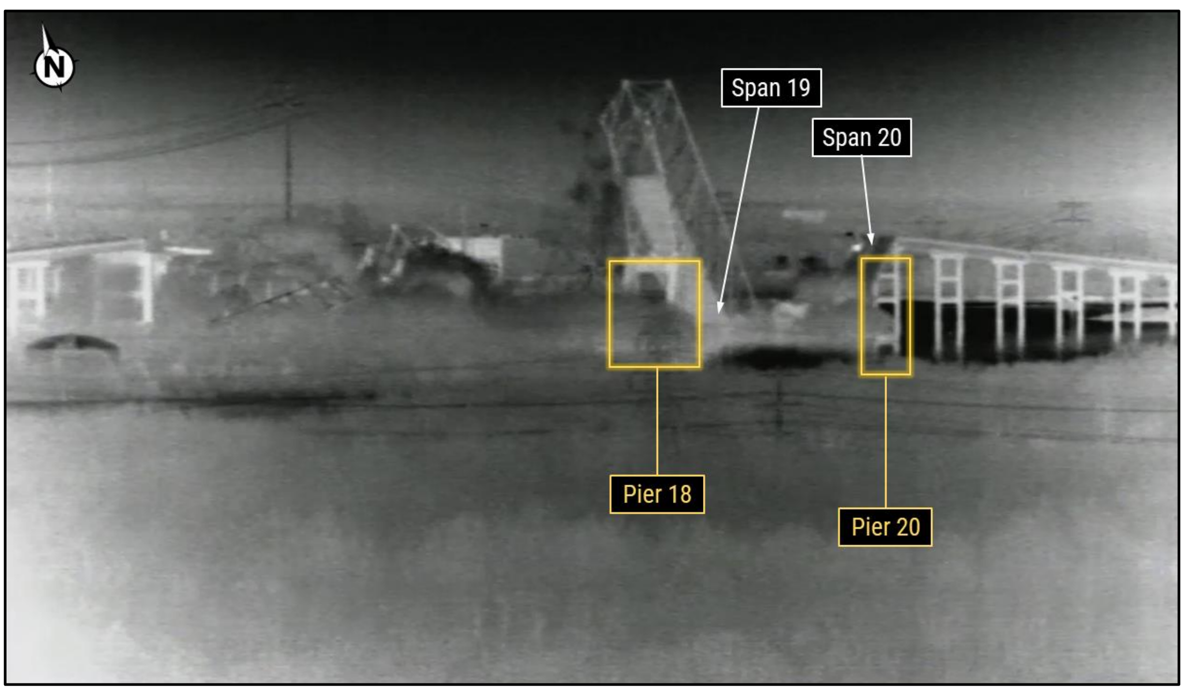

Figure 36. NRP video depicting the collapse of Pier 19 and Span 20.

Figure 37 depicts the collapse of Pier 20, Span 21, and Span 22.

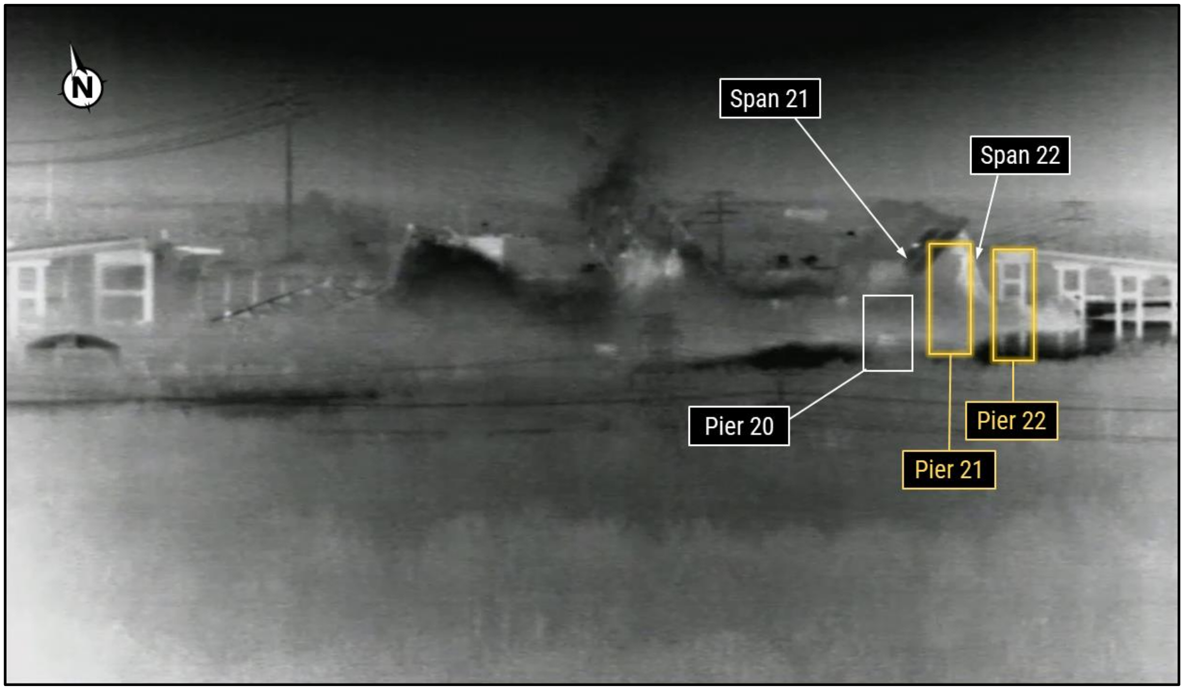

Figure 37. NRP video depicting the collapse of Pier 20, Span 21, and Span 22.

Figure 38 depicts the collapse of Pier 21. Span 16 and Span 23 were the spans that remained at each end of the bridge. Pier 16, Pier 18, and Pier 22 remained after the collapse.

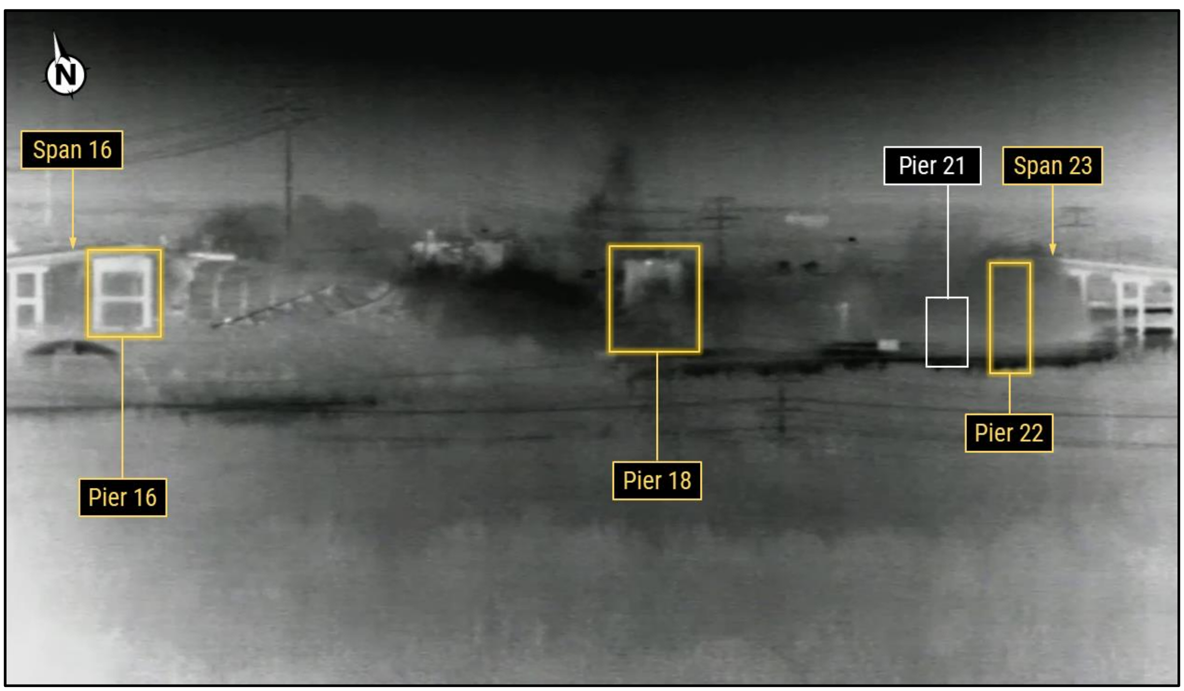

Figure 38. NRP video depicting the collapse of Pier 21.

Approximately 13 seconds after the starboard bow of the *Dali* impacted Pier 17, Pier 17 collapsed resulting in the subsequent collapse of the entire steel truss (including Span 17, Span 18, and Span 19), Pier 19, Pier 20, Pier 21, Span 20, Span 21, and Span 22. During the collision sequence, the *Dali* did not interact with any of the four dolphins or their rubber fenders protecting Pier 17 and Pier 18. Both fendering systems surrounding Pier 17 and Pier 18 were damaged during the collapse of the truss spans of the bridge when components of the truss spans impacted portions of the fenders as the components fell into the water.

Figure 39 illustrates the final rest position of the *Dali* and the locations of the four dolphins that protected Pier 17 and Pier 18.

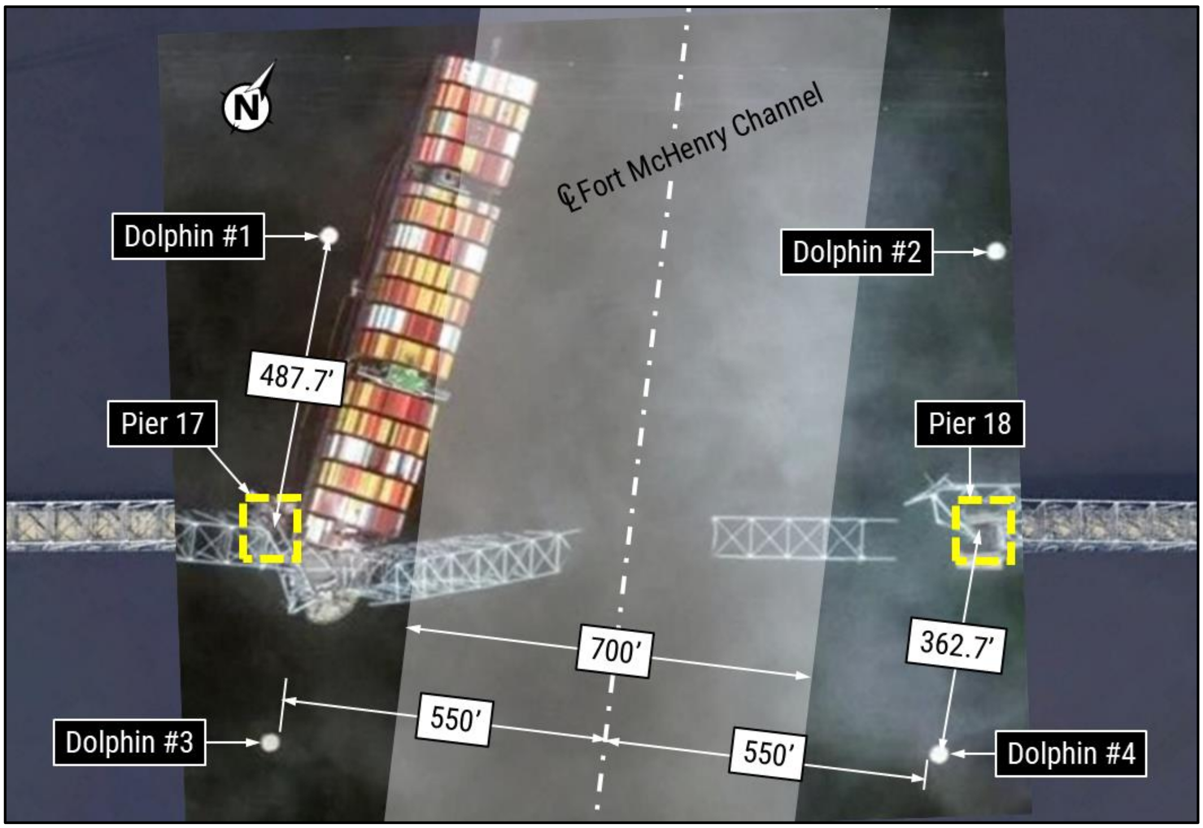

Figure 39. Navigation channel and locations of the dolphins (source: Maxar and Google Earth revised).

Figure 40 is a view from the edge of Span 16 looking to the north depicting the *Dali* with a portion of the Key Bridge resting on the bow and Dolphin #1 located along the starboard side of the vessel, forward of the stern.

Figure 40. Final rest position of the *Dali*.

G. RISK ASSESSMENT

1.0 Introduction

The American Association of State Highway and Transportation Officials (AASHTO) Guide Specifications and Commentary states the following:[33]

> *"AASHTO recognizes the potential that a significant portion of older bridges crossing navigable waterways in the Nation may not meet the risk acceptance criteria for new bridges contained in the AASHTO Specifications adopted since 1991. The intent of performing vessel collision vulnerability assessments on the existing bridge system is to identify those structures that are particularly vulnerable to catastrophic collapse. The vessel collision vulnerability information would provide a framework for States to be aware of high-risk safety needs requiring immediate or short-term action, as well as information to prioritize and budget for the long-term needs for bridge rehabilitation or replacement. The risk assessment of the existing bridges will be used as a part of the prioritization process and allocation of federal funds."*[34]

[33] See Section 1.1.3 – *Design Vessel* in AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges. 2nd Edition. Washington, DC, page 2.
[34] AASHTO has no authority in the allocation of federal funds.

AASHTO provides guidance on three alternative methods for conducting bridge risk assessments:[35]

- Method I – "*a semi-determinate procedure for selecting the design vessel for collision impact. Method I is the simplest of the three methods to use, but is also the most conservative, resulting in higher impact forces than those developed in Method II.*"[36]
- Method II – "*probability-based (risk) analysis procedure for selecting the design vessel for collision impact. Significantly more complicated than Method I, Method II requires a relatively large amount of data to conduct the analysis. The use of the Method II probability procedures results in a more realistic assessment of the risk of vessel collision with a bridge structure, and therefore a more accurate selection of the appropriate collision impact loads.*"
- Method III – "*a cost-effectiveness analysis procedure for selecting the design vessel for collision impact. The determination of annual frequency of bridge collapse, AF, required in Method III shall be computed using Method II. The disruption costs associated with a potential bridge collapse are evaluated using standard benefit/cost (B/C) analysis to determine the cost-effectiveness of bridge strengthening or bridge protection measures.*"

According to AASHTO, unless an existing bridge was designed in accordance with the previous 1991 edition of the AASHTO Vessel Collision Specifications, all remaining bridges over navigable waterways with commercial barge and ship traffic should be evaluated using a vulnerability assessment in accordance with the Method II risk analysis procedures contained in the current guide specifications.[37]

The MDTA had not performed a bridge risk assessment on the Key Bridge. In addition, the MDTA had not calculated the ultimate lateral pier resistance capacities, a necessary element in conducting a vulnerability assessment;[38] therefore, the NTSB conducted a vulnerability assessment of the Key Bridge utilizing Method II.

The purpose of this risk analysis was to calculate the annual frequency of collapse for the Key Bridge given the characteristics of the bridge at the time of its collapse to assess whether the calculated value was within an acceptable range. This

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[35] See Section C3.6 –*Design Vessel* in AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges. 2nd Edition. Washington, DC, pages 34-35.
[36] Method I should not generally be used for critical/essential bridges, deep draft waterways where large merchant ships comprise a significant portion of the total vessel traffic, and waterways where the distribution of vessel sizes (DWT) vary over a wide range of vessel types and sizes.
[37] See Section 1.1.3 – *Existing Bridges* in AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges. 2nd Edition. Washington, DC, page 2.
[38] See Bridge Protection Systems Attachment – Email from MDTA dated June 13, 2024.

analysis focused on Pier 16, Pier 17, Pier 18, and Pier 19, the piers that provided support to the continuous through truss over the main navigable channel.

Two factors are used to determine the operational classification of a bridge, social/survival evaluation, and security/defense evaluation. Bridges located on the Strategic Highway Network (STRAHNET) should be classified as critical essential bridges.[39] The Key Bridge was on the STRAHNET; therefore, it was a critical/essential bridge.

According to Method II, the acceptable annual frequency of collapse, $AF,$ of critical/essential bridges shall be equal to, or less than, 1 in 10,000 years (AF = 0.0001). The acceptable annual frequency of bridge collapse for the total bridge shall be distributed over the number of pier and span elements located within the waterway, or within the distance $3 \times LOA$ (length overall) on each side of the inbound and outbound vessel transit paths if the waterway is wide.[40] The annual frequency of bridge element collapse is calculated as follows:

$AF = (N)(PA)(PG)(PC)(PF)$ where:

- N = annual number of vessels classified by type, size, and loading condition which can strike the bridge element;
- PA = probability of vessel aberrancy;
- PG = geometric probability of a collision between an aberrant vessel and bridge pier or span;
- PC = probability of bridge collapse due to a collision with an aberrant vessel;
- PF = adjustment factor to account for potential protection of the piers from vessel collision due to upstream or downstream land masses, or other structures, which block the vessel.

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[39] The STRAHNET is an approximately 64,000-mile network of highways important for defense mobility and deployment of military equipment and personnel.
[40] See Section C3.6 – *Design Vessel* in AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges. 2nd Edition. Washington, DC, pages 34-35.

It should be noted that this risk assessment does not account for vessel traffic growth. According to NTSB Specialist's Study *Vessel Size Increase and Associated Safety Risks: A Review of the Scientific Literature and Publicly Available Data*:

- A review of Census Bureau data shows that the total weight of goods at U.S. ports has increased substantially over the past decade, with container ships driving that increase nationally.

- The total weight of imports and exports at all U.S. ports has increased from about 1.26 billion metric tons in 2013 to about 1.47 billion metric tons in 2023, a 16.7 percentage increase. For container ships, that growth is even more pronounced, with a 21.1 percentage increase from 246 million metric tons in 2013 to about 298 million metric tons in 2023.

- The Port of Baltimore has exhibited even more significant growth than the national average. The total weight of vessels at the Port of Baltimore increased by 71.7%, from about 27.6 million metric tons in 2013 to 47.4 million metric tons in 2023. The weight of container vessels at the Port of Baltimore increased by 61.3% during the same period, from about 5.17 million metric tons to roughly 8.34 million metric tons.

- The Port of Baltimore's growth is likely due in part to its ability to handle some of the largest container ships in the world. The port is one of only four Eastern U.S. ports with a 50-foot-deep shipping channel and a 50-foot-deep container berth.

Table 1 is a summary of total vessel imports and exports, both nationally and the Port of Baltimore between 2013 and 2023.

Table 1. *Total Vessel Imports and Exports: All U.S. Ports and the Port of Baltimore 2013-2023*

	National Vessel Weight (metric tons)		**Port of Baltimore Vessel Weight (metric tons)**	
Year	**All U.S. Vessels**	**Containerized**	**All Port Vessels**	**Containerized**
2013	1.26 billion	246 million	27.6 million	5.17 million
2014	1.29 billion	257 million	26.8 million	5.46 million
2015	1.27 billion	264 million	29.5 million	5.98 million
2016	1.28 billion	274 million	28.8 million	6.51 million
2017	1.39 billion	292 million	34.7 million	7.41 million
2018	1.45 billion	311 million	39.1 million	7.87 million
2019	1.40 billion	307 million	40.1 million	8.16 million
2020	1.34 billion	306 million	33.9 million	7.82 million
2021	1.44 billion	331 million	39.6 million	9.11 million
2022	1.48 billion	330 million	40.2 million	8.57 million
2023	1.47 billion	298 million	47.4 million	8.34 million

2.0 Vessel Frequency Distribution

2.1 Source Data

The AASHTO risk assessment calculation requires essential data including description of the vessel traffic passing under the bridge, vessel transit speeds, vessel loading characteristics, waterway and navigable channel geometry, water depths, environmental conditions, and bridge geometry. Data related to the vessel traffic and vessel characteristics for vessels traversing under the bridge was collected from various sources and compiled into a table within Microsoft Excel.

2.1.1 NOAA AccessAIS

Vessel traffic data, or Automatic Identification System (AIS) data, are collected by the U.S. Coast Guard through an onboard navigation safety device that transmits and monitors the location and characteristics of vessels in U.S. and international waters in real time. The Bureau of Ocean Energy Management, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Coast Guard Navigation Center have worked together to repurpose some of the most important records and make these records available to the public. These records are sourced from the U.S. Coast Guard's national network of AIS receivers called the Nationwide Automatic Identification System. Information such as location, time, vessel type, speed, length, beam, and draft have been extracted from the raw data and prepared for analyses in desktop geographic information system (GIS) software.

The publicly available NOAA web-based tool, AccessAIS,[41] provides data that includes, but are not limited to:

Maritime Mobile Service Identity (MMSI)	Vessel's international maritime telephone number
Base Date Time	Date and time of transit
Latitude and Longitude	GPS position of vessel
Speed Over Ground (SOG)	Speed of vessel in relation to fixed point on earth
Course Over Ground (COG)	Actual direction of vessel between two points
Heading	Compass direction in which the vessel's bow is pointed
Vessel Name	Formal vessel name that serves as a permanent identity
International Maritime Organization (IMO)	Unique seven-digit vessel identifier
Vessel ID	Unique combination of letters and/or numbers
Status	Numerical value from 0 to 15 related to vessel activity
Vessel Dimensions	Vessel length, width, and draft

[41] AccessAIS (noaa.gov)

2.1.2 Made Smart Group

Made Smart Group includes tools that can be integrated into geographical information systems as well as asset tracking and tracing systems. These tools enhance the visualization of geographic information with nautical charts in combination with, for example, weather maps, oceanography, sea-states, and aerial imagery. Made Smart Group also maintains a database with maritime AIS data in its original raw form as broadcast by ship borne AIS transponders since 2005. The AIS data contained in the data from Made Smart Group includes, but are not limited to:

MMSI	Vessel's international maritime telephone number
IMO	Unique seven-digit vessel identifier
Vessel Name	Formal vessel name that serves as a permanent identity
Call Sign	Used when communicating over the vessel's radio
Vessel Dimensions	Vessel length, width, and draft

2.1.3 Sea-Web

Within the Made Smart Group tools, a user can export data from Sea-web. Sea-web is a maritime reference tool, with more than 600 data fields on over 220,000 ships of 100 gross tonnage and above. Sea-web features multiple, separate modules that integrate detailed information on ships, companies, builders, ports, movements, fixtures, casualties, performance, security and more into one online platform. It features seven levels of ownership and more than 290,000 owners, 300,000 companies, 16,000 ports and 116,000 ship photographs. Data from Sea-web includes, but are not limited to:

Owner/operator	Vessel's owner and operator name
Vessel Type	General and detailed type of vessel
Vessel Dimensions	Vessel length, width, height, and draft
Loaded and Unloaded Displacement	Unloaded and loaded weight of the vessel
Gross Tonnage (GT)	Nonlinear measure of a vessel's internal volume
Deadweight Tonnage (DWT)	Weight of cargo, fuel, water and stores necessary to submerge a vessel from her light draft to her loaded draft
Design Speed (knots)	Fastest speed at which it is deemed safe for the vessel

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2.1.4 Internet Sources

If necessary, vessel information, particularly DWT, that was not able to be obtained through queries made in Made Smart Group and Sea-web, was obtained from internet sources, including Balticshipping.com and Shipspotting.com.[42]

Vessel data was queried by the unique 7-digit vessel identifier (IMO) or the vessel's international maritime telephone number (MMSI). Data obtained from the internet sources includes, but are not limited to:

MMSI	Vessel's international maritime telephone number
IMO	Unique seven-digit vessel identifier
Vessel Name	Formal vessel name that serves as a permanent identity
Vessel Type	Detailed type of vessel
Call Sign	Used when communicating over the vessel's radio
GT	Nonlinear measure of a vessel's internal volume
DWT	Weight of cargo, fuel, water and stores necessary to submerge a vessel from her light draft to her loaded draft
Vessel Dimensions	Vessel length, width, and draft

2.2 Use of the Data Sources

Each of the four data sources provided information on the vessel traffic and vessel parameters that were utilized in the risk analysis. The data sources were combined by first using AccessAIS to obtain vessel traffic between January 1, 2019, and March 26, 2024, by drawing a geofence box around the main channel of the Key Bridge (see **Figure 41**).

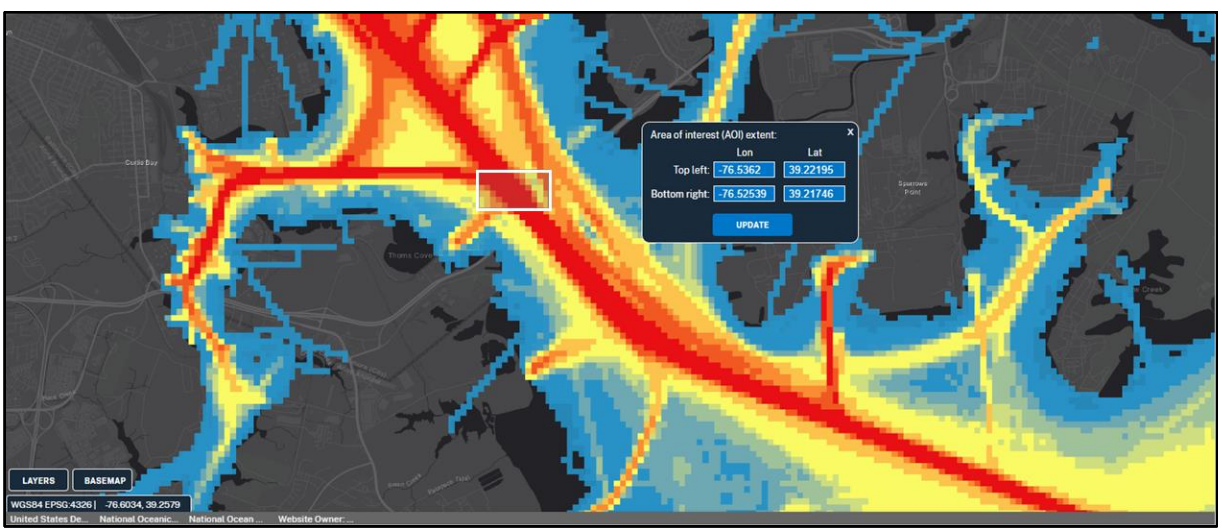

Figure 41. Screenshot from AccessAIS depicting the geofence box and coordinates of the limits.

[42] Note that the dead weight tonnage, DWT, is the weight the ship can carry. It does not include the weight of the ship itself.

The dataset obtained from AccessAIS contained 292,463 records; however, these records included all vessels transmitting AIS data, which included vessels other than ocean going ships, which is the class of vessel used in the risk analysis. The data were filtered to only include ocean-going ships, including container ships, general cargo ships, tankers, bulk carriers, and other vessels (passenger ships, cable laying ships, research ships, support ships, training ships, and U.S. Naval ships).[43]

In addition to the filtering of data to only include ocean-going ships, some of the vessel's transmitted AIS data was reported in short intervals resulting in numerous transmissions within the geofence box. Filtering the data to remove duplicate records that were transmitted within 15 minutes of each other resulted in 17,001 records. The 17,001 records included multiple transits by some of the same ocean-going vessels. The data was further refined and a total of 2,756 unique ocean-going vessels contributed to the 17,001 records.

Next, the IMOs of the 2,756 unique ocean-going vessels were imported into Made Smart Group server and web-based tools, which in turn queried the Sea-web database. A total of 2,645 detailed vessel parameters resulted from the IMO query.

Internet sources were utilized to determine the detailed vessel types and maximum DWTs of the 111 IMOs that did not match during the query. All 111 IMOs were matched using the internet sources and a complete dataset of 2,756 vessels that passed under the bridge during 2019-2024 was obtained through the various sources.

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[43] Although barges have been known to collide with bridge structures and barges were included in the AIS dataset, this analysis focused on ocean going ships.

2.3 Ocean-Going Vessel Transits 2019-2024

2.3.1 Volume

During the period between January 1, 2019, and March 26, 2024, there were a total of 17,001 transits by ocean going vessels through the main navigation channel through the Key Bridge (see **Table 2**). For reference, the *Dali* is a container ship with an overall length of 983.9 feet, beam (width) of 158.5 feet, a light displacement of 32,133 metric tons,[44] a DWT of 116,851 metric tons, and loaded displacement of 148,984 metric tons.

Table 2. *Summary of Ocean-Going Vessel Traffic (2019 to 2024)*

Year	Total	Container	Bulk Carrier	General Cargo	Tanker	Vehicles Carrier	Other
2019	**3,187**	720	593	389	185	1,087	213
2020	**2,478**	606	439	407	123	849	54
2021	**3,125**	728	668	514	213	958	44
2022	**3,480**	814	731	577	201	937	220
2023	**3,775**	1,032	873	575	187	891	217
2024[a]	**956**	232	205	201	40	229	49
Totals	**17,001**	4,132	3,509	2,663	949	4,951	797
Percentage		**24.3%**	**20.6%**	**15.7%**	**5.6%**	**29.1%**	**4.7%**

Note. [a]Only includes vessel traffic through March 26, 2024.

As can be seen in the table above, vehicles carriers (29.1%), container ships (24.3%), and bulk carriers (20.6%) account for most of the vessels passing under the bridge. While general cargo ships (15.7%), tankers (5.6%), and other ships (4.7%) account for the rest of the traffic.

There was a 25% decrease in the total number of vessel passages between 2019 and 2020. This was followed by a 23% increase in 2021, an 11% increase in 2022, and an 8% increase in 2023. This variation in vessel passages was likely attributed to the COVID-19 pandemic that began in March of 2020. Prior to the collapse of the bridge, during the first quarter in 2024, there were 956 vessel passages. If there was an average of 956 vessel passages for the remaining three quarters of 2024, there would have been an estimated 3,824 vessel passages in 2024.

[44] Light displacement is the weight of a vessel without cargo, fuel, passengers, crew, or ballast water on board, but still includes the weight of the vessel's hull, permanent machinery, and any necessary water in the system for operation.

2.3.2 Size and Weight of Vessel Traffic

Deadweight tonnage (DWT), the weight of cargo, fuel, water, and stores necessary to submerge a vessel from its light draft to its loaded draft, is used in the risk analysis to characterize vessels, primarily in the empirical function used to determine the force an impacting vessel will impart on a bridge pier.

The DWT, obtained from sources, represents the maximum DWT for each vessel; however, there are vessels, that if loaded to their maximum DWT capacity, would result in a draft (the vertical distance between the waterline and the bottom of the vessel's hull) that would prevent the vessel from ever reaching an evaluated bridge element or transiting via the main navigation channel.

As part of the AccessAIS data, draft of the vessel was reported; however, the DWT was not included in the data. To determine the DWT that would correlate to the recorded draft of the vessel, typical vessel characteristics were utilized to develop an equation to calculate DWT based upon the reported draft.[45]

Figure 42 illustrates typical vessel characteristics of a loaded vessel (left) and ballasted vessel (right). A ballasted vessel is a ship that is traveling without cargo and is carrying ballast to maintain stability.[46]

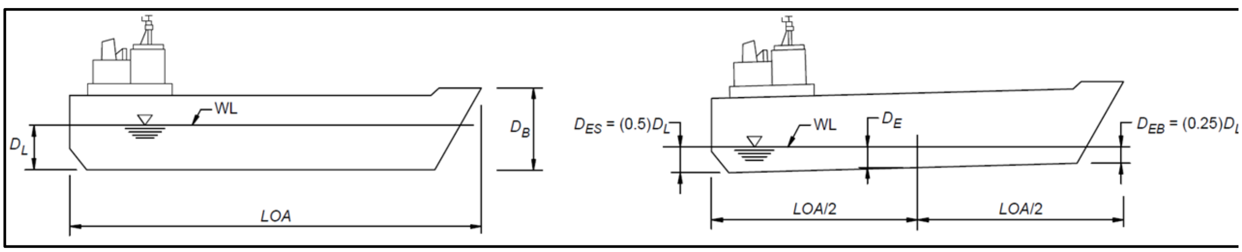

Figure 42. Vessel profiles of a loaded vessel (left) and ballasted vessel (right) (source: AASHTO)

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[45] See *Tables 3.5.2-1, 3.5.2-2, 3.5.2-3* in AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges. 2nd Edition. Washington, DC, pages 33-34.
[46] Ballast is a dense material, usually water, which is placed in a ship's ballast tanks to lower the ship's center of gravity and increase stability.

A plot of the DWT versus draft from the data contained within each of the AASHTO tables was developed, a 2nd order polynomial best fit regression line was established, and an equation was developed. The reported draft from the AccessAIS data was utilized in the equation and if the calculated DWT was less than the maximum DWT, the calculated DWT was utilized.

Table 3 contains typical freighter/container vessel characteristics that were relied upon to establish a plot and equation to calculate DWT based upon the draft reported in AccessAIS data for each vessel of this type (see **Figure 43**).

Table 3. *Typical Freighter/Container Characteristics (source: AASHTO)*

				Fully Loaded		Ballasted		
Ship *DWT*, tonnes	Length *LOA*, ft	Beam B_M, ft	Bow Depth, D_B	Draft D_L, ft	Displacement W_L, tonnes	Draft D_{EB}, ft	Draft D_{ES}, ft	Displacement W_E, tonnes
1,000	190	31.2	23.0	13.8	1,400	3.5	6.9	500
3,000	282	43.3	39.0	19.4	4,200	4.9	9.7	1,600
5,000	338	50.5	44.9	22.3	7,000	5.6	11.2	2,600
7,000	423	57.7	52.8	24.6	9,700	6.2	12.3	3,600
10,000	472	63.6	58.0	26.9	3,800	6.7	13.5	5,200
12,000	499	65.9	60.8	28.9	16,600	7.2	14.5	6,000
16,000	617	84.3	76.2	30.8	24,800	7.7	15.4	9,300
20,000	643	90.6	80.4	34.4	31,600	8.6	17.2	11,850
24,000	697	98.4	82.0	34.4	36,700	8.6	17.2	13,800
27,000	717	102.4	86.0	36.7	42,200	9.2	18.4	15,800
33,000	863	105.6	86.5	37.7	51,600	9.4	18.9	19,400
49,700	950	106.0	94.8	36.1	77,000	9.0	18.1	28,900
54,500	903	129.2	96.4	41.0	84,500	10.3	20.5	31,700

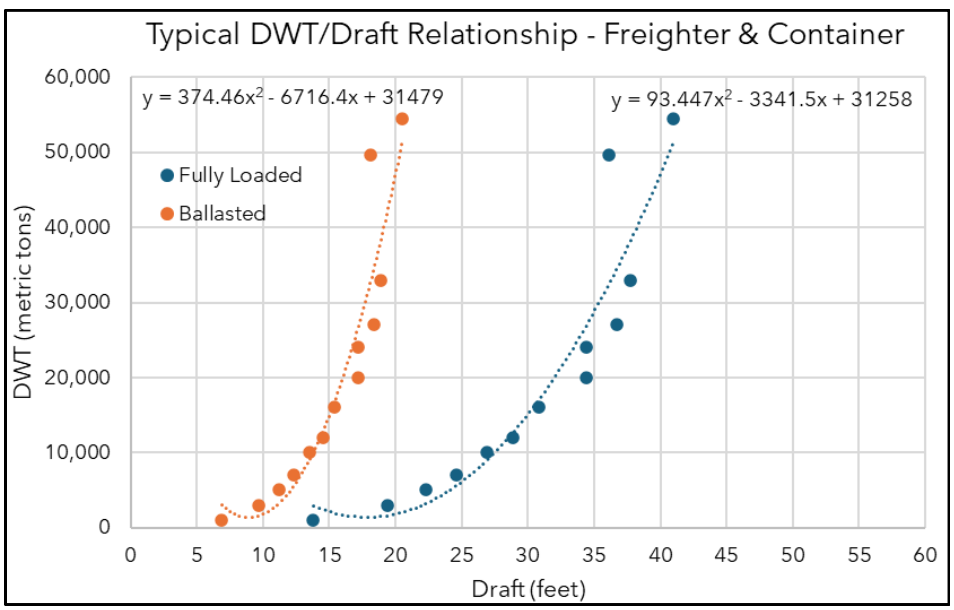

Figure 43. Plot of relationship between DWT to vessel draft for fully loaded and ballasted freighter/container ships along with a best fit equation.

Table 4 contains typical bulk carrier characteristics that were relied upon to establish a plot and equation to calculate DWT based upon the draft reported in AccessAIS data for each vessel of this type (see **Figure 44**).

Table 4. *Typical Bulk Carrier Characteristics (source: AASHTO)*

				Fully Loaded		Ballasted		
Ship *DWT*, tonnes	Length *LOA*, ft	Beam, B_M, ft	Bow Depth D_B	Draft D_L, (ft)	Displacement W_L, tonnes	Draft D_{EB}, ft	Draft D_{ES}, ft	Displacement W_E, tonnes
1,000	200	29.2	27.2	14.1	1,500	3.5	7.1	600
3,000	289	41.7	38.2	22.3	4,200	5.6	11.2	1,600
5,000	341	48.9	45.2	21.3	6,800	5.3	10.7	2,600
10,000	459	61.4	57.6	26.6	13,100	6.7	13.3	4,900
15,000	515	70.5	64.2	29.5	19,300	7.4	14.8	7,200
20,000	558	77.8	68.4	31.5	25,500	7.9	15.8	9,600
25,000	577	82.4	70.8	32.2	31,500	8.1	16.1	11,800
30,000	630	89.6	74.1	34.8	37,500	8.7	17.4	14,100
40,000	682	99.1	77.8	37.4	49,400	9.4	18.7	18,500
50,000	728	107.0	80.2	39.0	61,100	9.8	19.5	22,900
60,000	771	109.3	83.7	40.4	72,800	10.1	20.2	27,300
80,000	850	120.1	86.2	43.3	95,800	10.8	21.7	35,900
100,000	902	137.8	92.8	52.8	118,600	13.2	26.4	44,500
150,000	1027	146.0	99.7	59.1	174,700	14.8	29.6	65,500

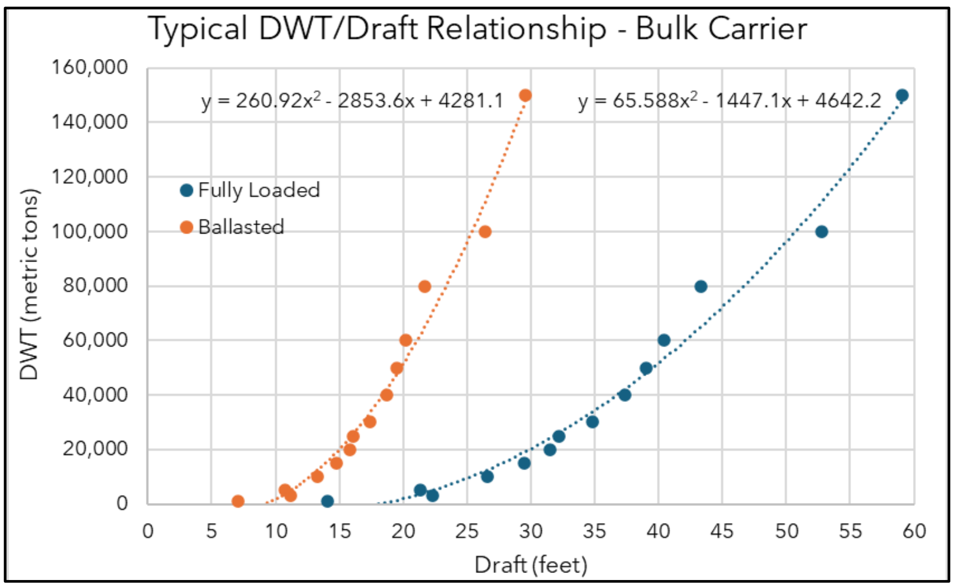

Figure 44. Plot of relationship between DWT to vessel draft for fully loaded and ballasted bulk carrier ships along with a best fit equation.

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Table 5 contains typical product carrier/tanker characteristics that were relied upon to establish a plot and equation to calculate DWT based upon the draft reported in AccessAIS data for each vessel of this type (see **Figure 45**).

Table 5. *Typical Product Carrier/Tanker Characteristics (source: AASHTO)*

				Fully Loaded		Ballasted		
Ship *DWT*, tonnes	Length *LOA*, ft	Beam B_M, ft	Bow Depth, D_B	Draft D_L, ft	Displacement W_L, tonnes	Draft D_{EB}, ft	Draft D_{ES}, ft	Displacement W_E, tonnes
1,000	187	30.8	25.0	13.8	1,400	3.5	6.9	500
3,000	279	42.0	35.4	19.4	4,100	4.9	9.7	1,500
5,000	335	48.2	41.8	22.6	6,700	5.7	11.3	2,500
10,000	456	62.3	53.6	26.6	13,000	6.7	13.3	4,900
15,000	515	71.2	60.2	29.5	19,300	7.4	14.8	7,200
20,000	561	78.1	65.1	32.2	25,400	8.1	16.1	9,500
25,000	577	83.7	68.7	33.1	31,500	8.3	16.6	11,800
30,000	637	89.2	71.7	34.8	37,500	8.7	17.4	14,100
40,000	692	98.1	75.8	38.4	49,500	9.6	19.2	18,600
50,000	741	105.3	78.5	41.0	61,400	0.3	20.5	23,000
60,000	774	111.5	81.8	42.0	73,200	0.5	21.0	27,500
80,000	853	122.4	83.6	45.6	96,500	11.4	22.8	36,200
100,000	886	128.0	85.0	47.9	119,700	12.0	24.0	44,900
120,000	915	138.9	88.2	50.9	142,600	12.7	25.5	53,500
150,000	955	145.0	90.6	58.7	176,800	14.7	29.4	66,300

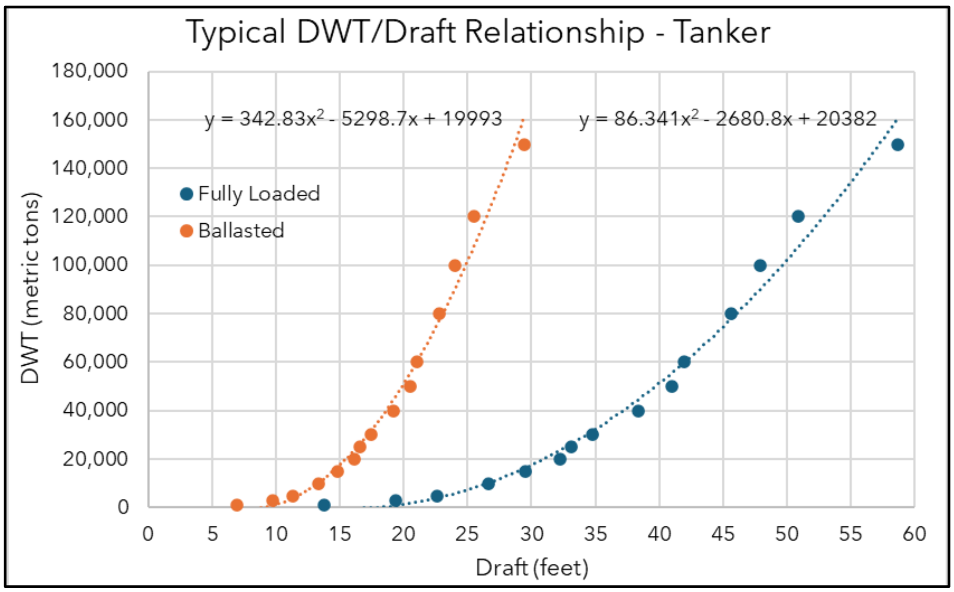

Figure 45. Plot of relationship between DWT to vessel draft for fully loaded and ballasted tanker ships along with a best fit equation.

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With DWTs calculated for all vessels, the composition of vessel traffic was developed and is presented in **Table 6** through **Table 11**.

Table 6 shows the annual number of passages by bulk carrier ships, categorized by DWT. The DWT of bulk carrier ships ranged between 517 and 180,745 metric tons.

Table 6. *Annual Number of Passages of Bulk Carrier Ships Categorized by DWT*

DWT (ton)	2019	2020	2021	2022	2023	2024
0 - 10,000	42	24	71	61	83	19
10 - 20,000	426	301	417	510	593	146
20 - 30,000	13	11	36	38	36	18
30 - 40,000	9	8	32	27	27	5
40 - 50,000	4	1	12	8	21	10
50 - 60,000	21	25	24	25	30	3
60 - 70,000	19	15	12	15	21	0
70 - 80,000	17	11	13	16	15	2
80 - 90,000	17	26	27	9	20	2
90 - 100,000	3	1	6	6	0	0
100 - 110,000	0	0	0	0	0	0
110 - 120,000	0	1	0	0	0	0
120 - 130,000	0	0	0	0	0	0
130 - 140,000	0	2	0	0	1	0
140 - 150,000	6	5	1	6	3	0
150 - 160,000	16	8	15	10	23	0
160 - 170,000	0	0	0	0	0	0
170 - 180,000	0	0	1	0	0	0
>180,000	0	0	1	0	0	0
Total	593	439	668	731	873	205

Table 7 shows the annual number of passages by general cargo ships, categorized by DWT. The DWT of general cargo ships ranged between 221 and 62,980 metric tons.

Table 7. *Annual Number of Passages of General Cargo Ships Categorized by DWT*

DWT (ton)	2019	2020	2021	2022	2023	2024
0 - 10,000	36	49	76	63	85	87
10 - 20,000	269	282	346	429	406	100
20 - 30,000	64	46	62	65	69	10
30 - 40,000	8	12	12	7	7	1
40 - 50,000	10	10	2	7	4	0
50 - 60,000	2	5	14	6	3	3
60 - 70,000	0	3	2	0	1	0
>70,000	0	0	0	0	0	0
Total	389	407	514	577	575	201

Table 8 shows the annual number of passages by container ships, categorized by DWT. The DWT of container ships ranged between 581 and 132,035 metric tons.

Table 8. *Annual Number of Passages of Container Ships Categorized by DWT*

DWT (ton)	2019	2020	2021	2022	2023	2024
0 - 10,000	24	16	8	5	8	0
10 - 20,000	514	434	430	577	706	170
20 - 30,000	19	20	35	33	71	17
30 - 40,000	9	15	36	56	55	19
40 - 50,000	11	24	109	43	52	8
50 - 60,000	15	16	25	23	32	6
60 - 70,000	17	16	16	20	34	10
70 - 80,000	45	28	17	13	9	2
80 - 90,000	39	19	27	28	38	0
90 - 100,000	14	9	12	11	21	0
100 - 110,000	12	9	11	5	6	0
110 - 120,000	1	0	1	0	0	0
>120,000	0	0	1	0	0	0
Total	720	606	728	814	1,032	232

Table 9 shows the annual number of passages by vehicles carrier ships, categorized by DWT. The DWT of vehicles carrier ships ranged between 2,294 and 48,988 metric tons.

Table 9. *Annual Number of Passages of Vehicles Carrier Ships Categorized by DWT*

DWT (ton)	2019	2020	2021	2022	2023	2024
0 - 10,000	33	29	39	34	31	13
10 - 20,000	855	685	763	735	716	194
20 - 30,000	127	98	113	130	113	22
30 - 40,000	62	28	30	31	22	0
40 - 50,000	10	9	13	7	9	0
>70,000	0	0	0	0	0	0
Total	1,087	849	958	937	891	229

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Table 10 shows the annual number of passages by tankers, categorized by DWT. The DWT of tankers ranged between 1,253 and 73,917 metric tons.

Table 10. *Annual Number of Passages of Tanker Vessels Categorized by DWT*

DWT (ton)	2019	2020	2021	2022	2023	2024
0 - 10,000	13	12	38	20	34	2
10 - 20,000	152	95	153	164	134	36
20 - 30,000	3	6	9	10	11	2
30 - 40,000	9	1	8	3	5	0
40 - 50,000	6	8	5	4	2	0
50 - 60,000	2	0	0	0	0	0
60 - 70,000	0	1	0	0	0	0
70 - 80,000	0	0	0	0	1	0
>80,000	0	0	0	0	0	0
Total	185	123	213	201	187	40

Table 11 shows the annual number of passages by other ships (passenger ships, cable laying ships, research ships, support ships, training ships, and U.S. Naval ships), categorized by DWT. The DWT of other ships ranged between 110 and 13,806 metric tons.

Table 11. *Annual Number of Passages of Other Vessels Categorized by DWT*

DWT (ton)	2019	2020	2021	2022	2023	2024
0 - 2,000	1	0	0	8	5	3
2 - 4,000	5	7	0	0	1	0
4 - 6,000	0	0	2	0	9	3
6 - 8,000	187	33	31	184	127	21
8 - 10,000	4	4	5	6	73	20
10 - 12,000	14	10	6	19	1	2
12 - 14,000	2	0	0	3	1	0
>14,000	0	0	0	0	0	0
Total	213	54	44	220	217	49

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3.0 Waterway Characteristics

3.1 Channel Layout

The geometry of the navigable channels near the Key Bridge was evaluated using an electronic nautical chart obtained from NOAA (see **Figure 46**) along with design plans for the bridge.

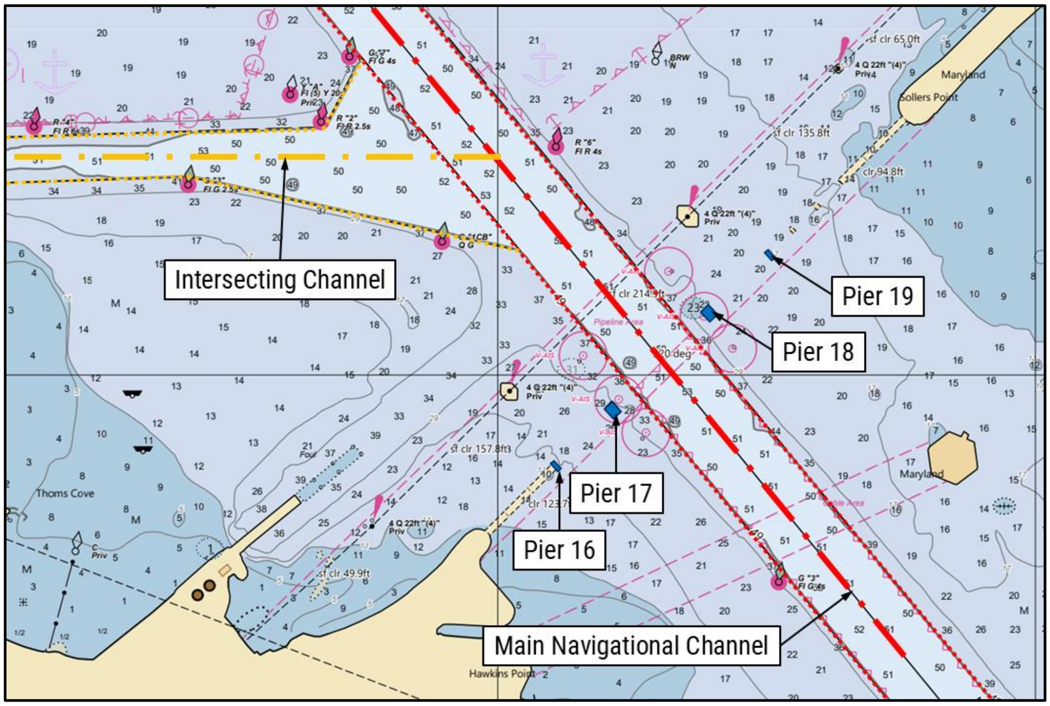

Figure 46. Nautical chart used to evaluate the channel layout.

Fort McHenry Channel was a 700-foot-wide main navigation channel that passed under the bridge. The main navigational channel in the vicinity of the bridge was straight, and there were no bends or turns. Curtis Bay Channel was an intersecting channel northwest of the bridge having a bend of approximately 50 degrees; however, the main channel remained straight.

According to the Association of Maryland Pilots (AMP), although the width of the channel would accommodate meeting or passing ocean-going vessels; this was avoided and would be a rare occurrence. Ocean-going vessels passed under the bridge at the centerline of the navigational channel.

3.2 Limiting Depth

The limiting depth is the maximum allowable depth of water a ship can safely navigate in, which is usually determined by the depth of the waterway it is entering. If the ship's draft is more than the limiting depth, the ship would ground and not be able to continue. If maximum DWTs were relied upon, remembering that DWT is the maximum weight that the ship can carry, some of the vessels, if loaded to their DWT capacity, would result in a draft that would prevent the vessel from ever reaching an evaluated bridge element or transiting via the main navigation channel.

An electronic nautical chart obtained from NOAA and information received from the AMP was relied upon to determine the limiting depths at the main channel, Pier 16, Pier 17, Pier 18, and Pier 19. Depths located within 400 feet of the bridge element were considered the limiting depth (see **Figure 47**: black circles).[47] This would account for a vessel running aground, but not immediately being stopped due to the momentum the vessel carried.

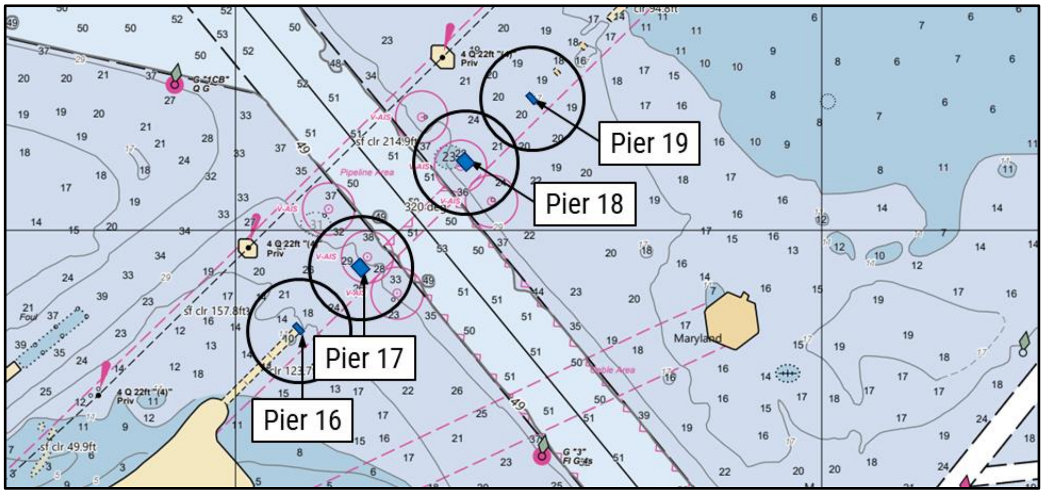

Figure 47. Nautical chart used to determine limiting drafts.

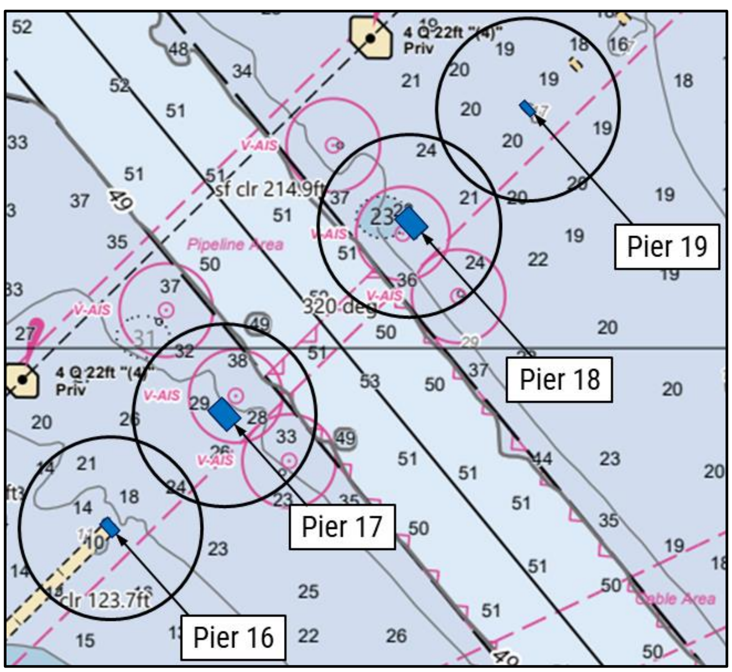

Figure 48. Close-up of Figure 47.

[47] It is recognized that if the 400-foot radius is increased it would increase the number of vessels capable of reaching Pier 16 and Pier 19; however, the influence the two piers have on the overall AF is minimal.

According to AMP, the maintained channel depth of the main navigational channel was 50 feet and the maximum allowable draft at zero tide level was 47 feet and up to 47 feet 6 inches with a plus 6-inch water level.

Table 12 is a summary of the limiting depths and corresponding bridge elements.

Table 12. *Limiting Depths*

Element	Limiting Depth (feet)
Main Channel	47
Pier 16	24
Pier 17	47
Pier 18	47
Pier 19	20

3.3 Currents

According to the AMP, the currents around the Key Bridge are negligible and easily overwhelmed by a prolonged wind event. Therefore, it is assumed there is no current around the bridge that would disrupt navigational control of vessels.

4.0 Annual Frequency of Collapse Calculations

4.1 Vessel Frequency (*N*)

The risk assessment was performed based upon the vessel traffic from the year 2023. Given the likelihood that vessel traffic between 2019 and 2022 was affected by the COVID Pandemic and not representative of annual vessel traffic prior to the bridge collapse, vessel traffic from 2023 would most closely be representative of the annual traffic prior to the collapse of the bridge and less affected by the COVID Pandemic.

The vessel traffic from 2023 was divided into six vessel groups: Container, Bulk Carrier, General Cargo, Tanker, Vehicles Carrier, and Other. The passages of individual vessels within each group were further categorized according to DWT. For simplicity of the calculations, the average DWT of the ranges presented in Table 6 through Table 11 was utilized for Pier 17 and Pier 18, while the maximum DWTs that correlated with the limiting draft for each vessel category were utilized for Pier 16 and Pier 19. For Pier 17 and Pier 18, if a vessel's DWT resulted in a draft that exceeded the limiting depth, it was placed in the DWT range within the limiting depth of the navigational channel (47 feet).

For Pier 16 and Pier 19, where the depth of the water was 24 and 20 feet respectively, vessels that exceeded the limiting depth were excluded in the vessel frequency. The two piers were located over 1,300 feet from the centerline of the navigational channel and would possibly run aground before reaching those piers.

The length overall (LOA) and beam (width) shown in the tables are the average dimension for all vessels within the DWT category.

4.1.1 Pier 16

The limiting depth for Pier 16 was 24 feet. Utilizing the equations developed in Section 2.3.2 and using a draft of 24 feet, computations resulted in DWTs of 4,887 metric tons for container ships and vehicles carriers, 5,775 metric tons for tankers, and 7,690 metric tons for bulk carriers, general cargo, and other vessels. **Table 13** contains the vessel frequency for Pier 16 only including ships with DWT values below the limiting depth, including both inbound and outbound trips. The overall length of the vessel and the beam are also listed.

Table 13. *Vessel Frequency for Pier 16*

Vessel ID	Vessel Type	DWT (tons)	Transits (N)			Dimensions (ft)	
			Inbound	Outbound	Total	LOA	Beam
1	Container	4,887	4	4	8	798	110
2	Bulk Carrier	7,690	36	36	72	946	148
3	General Cargo	7,690	20	19	39	904	122
4	Vehicles Carrier	4,887	14	14	28	935	125
5	Tanker	5,775	14	13	27	933	126
6	Other	1,000	3	2	5	1,070	147
7	Other	3,000	1	0	1	1,001	130
8	Other	5,000	5	4	9	1,029	139
9	Other	7,690	64	63	127	1,052	141
		Total	161	155	316		

4.1.2 Pier 17 and Pier 18

Table 14 contains the vessel frequency for Pier 17 and Pier 18, including both inbound and outbound trips. The overall length of the vessel and the beam are also listed.

Table 14. Vessel Frequency for Pier 17 and Pier 18

Vessel ID	Vessel Type	DWT (tons)	Transits (N)			Dimensions (ft)	
			Inbound	Outbound	Total	LOA	Beam
1	Container	5,000	4	4	8	798	110
2	Container	15,000	353	353	706	946	148
3	Container	25,000	36	35	71	904	122
4	Container	35,000	28	27	55	935	125
5	Container	45,000	26	26	52	933	126
6	Container	55,000	16	16	32	1,070	147

(*table continues*)

Vessel ID	Vessel Type	DWT (tons)	Transits (N)			Dimensions (ft)	
			Inbound	Outbound	Total	LOA	Beam
7	Container	65,000	17	17	34	1,001	130
8	Container	75,000	5	4	9	1,029	139
9	Container	85,000	19	19	38	1,052	141
10	Container	95,000	11	10	21	1,155	143
11	Container	105,000	3	3	6	1,183	145
12	Bulk Carrier	5,000	42	41	83	718	106
13	Bulk Carrier	15,000	297	296	593	930	145
14	Bulk Carrier	25,000	18	18	36	623	99
15	Bulk Carrier	35,000	14	13	27	804	122
16	Bulk Carrier	45,000	11	10	21	933	126
17	Bulk Carrier	55,000	15	15	30	1,070	147
18	Bulk Carrier	65,000	11	10	21	1,001	130
19	Bulk Carrier	75,000	8	7	15	1,029	139
20	Bulk Carrier	85,000	10	10	20	1,052	141
21	Bulk Carrier	95,000	14	13	27	1,183	145
22	General Cargo	5,000	43	42	85	743	115
23	General Cargo	15,000	203	203	406	876	136
24	General Cargo	25,000	35	34	69	633	92
25	General Cargo	35,000	4	3	7	632	98
26	General Cargo	45,000	2	2	4	653	100
27	General Cargo	55,000	2	1	3	642	105
28	General Cargo	65,000	1	0	1	798	110
29	Vehicles Carrier	5,000	16	15	31	946	148
30	Vehicles Carrier	15,000	358	358	716	904	122
31	Vehicles Carrier	25,000	57	56	113	935	125
32	Vehicles Carrier	35,000	11	11	22	933	126
33	Vehicles Carrier	45,000	5	4	9	1,070	147
34	Tanker	5,000	17	17	34	1,001	130
35	Tanker	15,000	67	67	134	1,029	139
36	Tanker	25,000	6	5	11	1,052	141
37	Tanker	35,000	3	2	5	1,155	143
38	Tanker	45,000	1	1	2	1,183	145
39	Tanker	75,000	1	0	1	718	106
40	Other	1,000	3	2	5	930	145
41	Other	3,000	1	0	1	623	99
42	Other	5,000	5	4	9	804	122
43	Other	7,000	64	63	127	933	126
44	Other	9,000	37	36	73	1,070	147
45	Other	11,000	1	0	1	1,001	130
46	Other	13,000	1	0	1	1,029	139
		Total	1,902	1,873	3,775		

4.1.3 Pier 19

The limiting depth for Pier 19 was 20 feet. Utilizing the equations developed in Section 2.3.2 and using a draft of 20 feet, computations resulted in DWTs resulting in 1,807 metric tons for container ships and vehicles carriers, 1,302 metric tons for tankers, and 1,935 metric tons for bulk carriers, general cargo, and other vessels. **Table 15** contains the vessel frequency for Pier 19 only including ships with DWT values below the limiting depth, including both inbound and outbound trips. The overall length of the vessel and the beam are also listed.

Table 15. *Vessel Frequency for Pier 19*

Vessel ID	Vessel Type	DWT (tons)	Transits (N)			Dimensions (ft)	
			Inbound	Outbound	Total	LOA	Beam
1	Bulk Carrier	1,935	3	2	5	798	110
2	General Cargo	1,935	3	2	5	946	148
3	Other	1,935	3	2	5	904	122
		Total	9	6	15		

4.2 Probability of Aberrancy (PA)

The probability of vessel aberrancy, PA, is a value related to the statistical probability that a vessel will stray off-course and threaten the bridge and is usually the result of navigation error, adverse environmental conditions, or mechanical failure.

The most accurate method of determining PA for a particular bridge site is based on historical data on vessel collisions, ramming, stranding and groundings in the waterway, and the number of vessels transiting the waterway during the period of accident reporting.

In lieu of the above method, the probability of aberrancy can be calculated as follows:

$PA = BR(R_B)(R_C)(R_{XC})(R_D)$ where:

BR = aberrancy base rate
R_B = correction factor for bridge location;
R_C = correction factor for current acting parallel to vessel transit path;
R_{XC} = correction factor for crosscurrents acting perpendicular to vessel transit paths;
R_D = Correction factor for vessel traffic density.

Based on historical accident data from several U.S. waterways, the base rate, BR, is 0.6×10^{-4} for ships.

The Key Bridge was in a straight region; however, there was an intersecting deep-water channel having a bend of approximately 50 degrees within the immediate vicinity of the bridge. The correction factor for bridge location, R_B, for a bridge located in a bend region was calculated as follows:

$$R_B = \left(1 + \frac{\theta}{45°}\right) = \left(1 + \frac{50°}{45°}\right) = 2.1$$

The current at the bridge was negligible; therefore, the correction factors for currents acting parallel to the vessel transit path, R_C, and crosscurrents, R_{XC}, is 1.0.

Ocean-going vessels rarely, if ever, meet, pass, or overtake each other in the immediate vicinity of the bridge; therefore, the correction factor for vessel traffic density, R_D, is 1.0.

The probability of aberrancy was calculated as follows:

$$PA = BR(R_B)(R_C)(R_{XC})(R_D) = 0.6 \times 10^{-4}(2.1)(1.0)(1.0)(1.0) = 1.3 \times 10^{-4}$$

According to AASHTO's Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges, a previous study established that the PA value for the Key Bridge is 1.0×10^{-4} for ships (see **Figure 49**). This means that there is a 1 in 10,000 probability that a vessel will go aberrant in the vicinity of the bridge.

Locality	Type of Data	Probability of Vessel Aberrancy ($\times 10^{-4}$)
Dover Straits—Collisions (MacDuff, 1974)	Statistics	5 to 7
Dover Straits—Groundings (MacDuff, 1974)	Statistics	1.4 to 1.6
Japanese Straits—Groundings (Fujii et al., 1974)	Statistics	0.7 to 6.7
Japanese Straits—Collisions (Fujii et al., 1974)	Statistics	1.3
Worldwide (Maunsell and Partners, 1979)	Statistics	0.5
Tasman Bridge, Australia (Leslie, 1979)	Estimate	0.6 to 1.0
Great Belt Bridge, Denmark (Cowinconsult, 1978)	Estimate	0.4
Sunshine Skyway Bridge, Florida (Greiner Engineering Sciences, 1985)	Statistics Statistics	1.3 (Ships) 2.0 (Barges)
Annacis Island Bridge, Canada (CBA/Buckland and Taylor, 1982)	Estimate	3.6
Francis Scott Key Bridge and William Preston Lane Bridges, Maryland (Greiner Engineering Sciences, 1983)	Statistics	1.0 (Ships) 2.0 (Barges)
Dames Point Bridge, Florida (Greiner Engineering Sciences, 1984)	Statistics	1.3 (Ships) 4.1 (Barges)
Laviolette Bridge, Canada (Greiner Engineering Sciences, 1984)	Statistics	0.5
Centennial Bridge, Canada (Greiner Engineering Sciences, 1986)	Statistics	5.0
Louisiana Waterways (Philipson, 1983)	Statistics	0.8 to 1.9 (Ships) 1.5 to 3.0 (Barges)
Gibraltar Straits—Strandings, Morocco (Modjeski and Masters Consulting Engineers, 1985)	Statistics	2.2
Gibraltar Straits—Collision, Morocco (Modjeski and Masters Consulting Engineers, 1985)	Statistics	1.2

Figure 49. Summary of *PA* values (source: AASHTO).

It should be noted that the bend created by the intersecting channel would only affect outbound vessels which would account for half of all vessels that would navigate the intersecting channel. For the purposes of the risk assessment, AASHTO's PA value of 1.0×10^{-4} was utilized during the risk assessment.

4.3 Geometric Probability (*PG*)

The geometric probability, PG, is defined as the conditional probability that a vessel will hit a bridge pier or superstructure component, given that it has lost control (i.e., it is aberrant) in the vicinity of the bridge.[48] The geometric probability is computed based on a normal distribution of aberrant vessel transit paths about the centerline of the vessel transit path as shown in **Figure 50**.

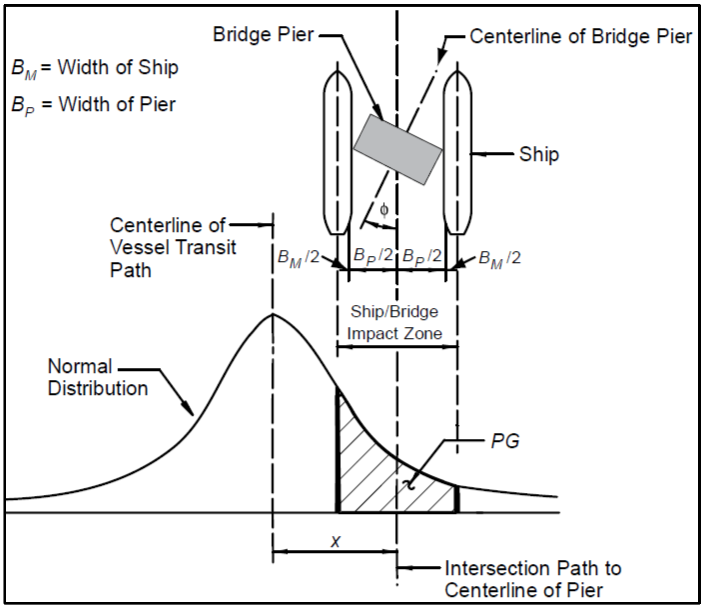

Figure 50. Parameters necessary to determine the geometric probability.

The geometric probability is equivalent to the area under the normal distribution bounded by the pier width and the width of the vessel on each side of the pier. The standard deviation, σ, of the normal distribution is assumed to be equal to the length overall, LOA, of the vessels in the design fleet. The location of the mean, μ, of the normal distribution is taken at the centerline of the vessel transit path. The value of PG is computed based on the width (beam), B_M, of each vessel classification category.

Although the centerline bearing of the Fort McHenry Navigational Channel was not perpendicular to the Key Bridge, the angle was negligible and would have had a minimal effect on the width of the analyzed pier; therefore, the actual width of the analyzed pier was used in the calculations.

48 See Section C3.14.5.3 – *Geometric Probability* in AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges. 2nd Edition. Washington, DC, page 3-158.

Table 16 depicts the distance, x, between the centerline of the navigational channel and the centerline of each analyzed pier. The distances were based upon design plans of the bridge, with the centerline of the navigational channel intersecting the bridge at Station 492+05.150.

Table 16. *Pier to Navigational Channel Distances*

Pier	Pier Width (B_P)	Station	x (feet)
16	47 feet	478+83.567	1,322
17	86 feet	486+05.150	600
18	86 feet	498+05.150	600
19	47 feet	505+26.733	1,322

Figure 51 is a plan view of the Main Spans of the Key Bridge illustrating the distance, x, between the centerline of the navigational channel and the centerline of each analyzed pier.

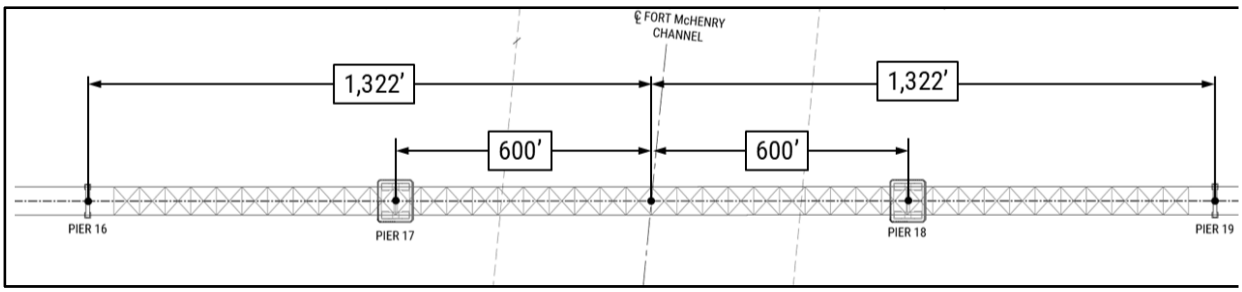

Figure 51. Distances between centerlines of the channel and analyzed piers.

Next, the left, x_L, and the right, x_R, bounds of the normal distribution were determined based upon the width, B_P, of the pier, and the breadth, B_M, of each vessel category using the equations below.

$$x_L = x - \frac{(B_M + B_P)}{2} \qquad x_R = x + \frac{(B_M + B_P)}{2}$$

Next, the left and right bounds, x_L and x_R, of the normal distribution, which had a standard deviation, σ, equivalent to the length overall of each vessel category, and a mean, μ, of 0 feet, was utilized to calculate the corresponding z-scores as follows:

$$z_L = \frac{x_L - \mu}{\sigma} \qquad z_R = \frac{x_R - \mu}{\sigma}$$

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The corresponding z-scores were used as inputs in the normal distribution (NORMSDIST) function within Excel. The result of the NORMSDIST function represents the area under the normal distribution curve to the left of the respective z-score. The difference between the two areas represented by the left and right z-score are equivalent to the area bound by the same. As an example, the left and right z-score for Vessel ID #1 in **Table 17** is 1.56 and 1.76 respectively. The NORMSDIST function returns a value of 0.9406 and 0.9608 respectively.[49] The difference between the two values, 0.0202 represents the area under the normal distribution curve, or *PG*, as shown in **Figure 50.**

Using Microsoft Excel, the geometric probability, PG, for Pier 16 and each vessel category is presented in **Table 17**.

Table 17. *Geometric Probability for Pier 16*

Vessel ID	Vessel Type	Beam B_M (ft)	LOA σ (ft)	x_L (ft)	x_R (ft)	z_L	z_R	PG
1	Container	110	798	1,243	1,401	1.56	1.76	0.0202
2	Bulk Carrier	106	712	1,245	1,399	1.75	1.97	0.0156
3	General Cargo	104	673	1,246	1,398	1.85	2.08	0.0134
4	Vehicles Carrier	118	653	1,240	1,405	1.90	2.15	0.0129
5	Tanker	85	498	1,256	1,388	2.52	2.79	0.0032
6	Other	148	948	1,225	1,420	1.29	1.50	0.0317
7	Other	85	738	1,256	1,388	1.70	1.88	0.0145
8	Other	136	928	1,231	1,413	1.33	1.52	0.0275
9	Other	142	952	1,227	1,417	1.29	1.49	0.0304

The geometric probability, PG, for Pier 17 and Pier 18 and each vessel category was computed and is presented in **Table 18**.

Table 18. *Geometric Probability for Pier 17 and Pier 18*

Vessel ID	Vessel Type	Beam B_M (ft)	LOA σ (ft)	x_L (ft)	x_R (ft)	z_L	z_R	PG
1	Container	110	798	502	698	0.63	0.87	0.0722
2	Container	148	946	483	717	0.51	0.76	0.0814
3	Container	122	904	496	704	0.55	0.78	0.0735
4	Container	125	935	495	705	0.53	0.75	0.0714
5	Container	126	933	494	706	0.53	0.76	0.0744
6	Container	147	1,070	483	717	0.45	0.67	0.0749
7	Container	130	1,001	492	708	0.49	0.71	0.0732
8	Container	139	1,029	488	713	0.47	0.69	0.0741
9	Container	141	1,052	486	714	0.46	0.68	0.0745
10	Container	143	1,155	486	714	0.42	0.62	0.0696
11	Container	145	1,183	485	715	0.41	0.60	0.0666

(*table continues*)

[49] A Z table can also be used.

Vessel ID	Vessel Type	Beam B_M (ft)	LOA σ (ft)	x_L (ft)	x_R (ft)	z_L	z_R	PG
12	Bulk Carrier	106	718	504	696	0.70	0.97	0.0759
13	Bulk Carrier	145	930	484	716	0.52	0.77	0.0809
14	Bulk Carrier	99	623	508	692	0.81	1.11	0.0755
15	Bulk Carrier	122	804	496	704	0.62	0.88	0.0782
16	Bulk Carrier	126	933	494	706	0.53	0.76	0.0744
17	Bulk Carrier	147	1,070	483	717	0.45	0.67	0.0749
18	Bulk Carrier	130	1,001	492	708	0.49	0.71	0.0732
19	Bulk Carrier	139	1,029	488	713	0.47	0.69	0.0741
20	Bulk Carrier	141	1,052	486	714	0.46	0.68	0.0745
21	Bulk Carrier	145	1,183	485	715	0.41	0.60	0.0666
22	General Cargo	115	743	500	700	0.67	0.94	0.0778
23	General Cargo	136	876	489	711	0.56	0.81	0.0788
24	General Cargo	92	633	511	689	0.81	1.09	0.0711
25	General Cargo	98	632	508	692	0.80	1.09	0.0740
26	General Cargo	100	653	507	693	0.78	1.06	0.0731
27	General Cargo	105	642	505	696	0.79	1.08	0.0747
28	General Cargo	105	653	505	696	0.77	1.07	0.0783
29	Vehicles Carrier	103	641	506	695	0.79	1.08	0.0747
30	Vehicles Carrier	139	885	488	712	0.55	0.80	0.0793
31	Vehicles Carrier	107	685	504	696	0.74	1.02	0.0758
32	Vehicles Carrier	105	760	505	696	0.66	0.92	0.0758
33	Vehicles Carrier	106	866	504	696	0.58	0.80	0.0691
34	Tanker	102	577	506	694	0.88	1.20	0.0744
35	Tanker	137	869	489	711	0.56	0.82	0.0816
36	Tanker	121	563	496	704	0.88	1.25	0.0838
37	Tanker	103	584	505	695	0.86	1.19	0.0779
38	Tanker	107	673	504	696	0.75	1.03	0.0751
39	Tanker	105	748	505	696	0.68	0.93	0.0721
40	Other	148	948	483	717	0.51	0.76	0.0814
41	Other	85	738	515	686	0.70	0.93	0.0658
42	Other	136	928	489	711	0.53	0.77	0.0774
43	Other	142	952	486	714	0.51	0.75	0.0784
44	Other	142	940	486	714	0.52	0.76	0.0779
45	Other	148	948	483	717	0.51	0.76	0.0814
46	Other	148	948	483	717	0.51	0.76	0.0814

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The geometric probability, PG, for Pier 19 and each vessel category is presented in **Table 19**.

Table 19. *Geometric Probability for Pier 19*

Vessel ID	Vessel Type	Beam B_M (ft)	LOA σ (ft)	x_L (ft)	x_R (ft)	z_L	z_R	PG
1	Bulk Carrier	105	656	1,246	1,398	1.90	2.13	0.0121
2	General Cargo	104	673	1,246	1,398	1.85	2.08	0.0134
3	Other	148	948	1,225	1,420	1.29	1.50	0.0317

4.4 Probability of Collapse (*PC*)

The probability of bridge collapse, PC, once a bridge element has been struck by an aberrant vessel is dependent on the vessel impact force (P), which is a function of many variables, including vessel size, type, forepeak ballast and shape, speed, direction of impact, and mass. It is also dependent on the ultimate lateral capacity of the pier, H_P, and span, H_S, to resist collision impact loads.[50]

Based on historical accident data, the probability of collapse is computed according to the ratio of the ultimate lateral capacity of the analyzed pier (H_P) to the vessel impact force (P) as follows:

For H_p/P between 0.0 and 0.1, PC is computed as:[51]

$$PC = 0.1 + 9\left(0.1 - \frac{H_P}{P}\right)$$

For $0.1 \le H_p/P < 1.0$, PC is computed as:[52]

$$PC = \left(1.0 - \frac{H_P}{P}\right)(0.111)$$

The impact speed used to determine the impact force for each exposed bridge element in the waterway shall be determined based on the typical vessel transit speed within the navigable channel limits, the distance to the location of the bridge element from the centerline of the vessel transit path, and the overall length of the vessel (LOA).

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[50] H_p was used in these calculations since the pier was impacted by the Dali. PC based on H_s would be calculated in instances such as where the top of a ship impacted the span of the bridge.

[51] See Section 4.8.3.4 – *Probability of Collapse (PC)* in AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges. 2nd Edition. Washington, DC, page 75

[52] See Section 4.8.3.4 – *Probability of Collapse (PC)* in AASHTO 2010 Interim Edition to the Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges. 2nd Edition. Washington, DC, page 11

The AASHTO Guide Specifications recommends the use of a triangular distribution of vessel impact speed across the length of the bridge and centered on the centerline of the vessel transit path (see **Figure 52**).

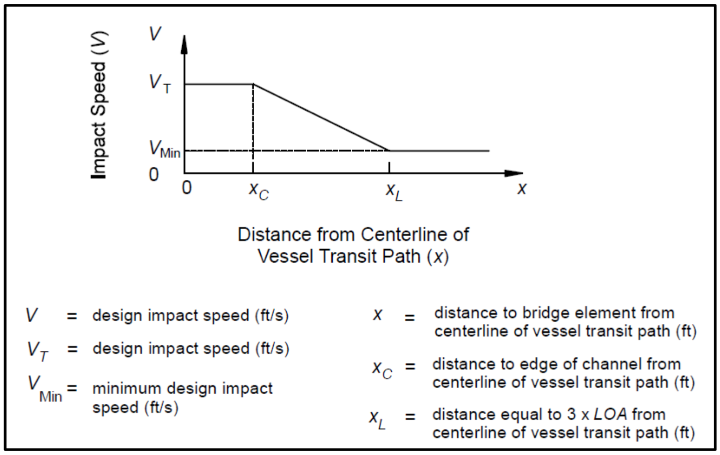


Figure 52. Triangular distribution used to calculate impact speed.

The distance from the centerline of the vessel transit path (centerline of the navigational channel) and the edge of the channel was $X_C = 350$ feet. The distance from the centerline of the vessel transit path to the bridge element was $X = 550$ feet for Pier 17 and Pier 18, and $X = 1{,}315$ feet for Pier 16 and Pier 19. The distance equal to 3 times the LOA from the centerline of the vessel transit path varied based on the LOA of each vessel category.

The AccessAIS data contained the speed over ground (knots) of each vessel. This data was relied upon to determine the average typical speed (V_T) of each vessel type.

Table 20 contains the vessel speeds used in the calculations.

Table 20. *Average Typical Vessel Speeds*

Vessel Type	Vessel Speed	
	Knots	Feet Per Second
Container	8.3	14.0
Bulk Carrier	8.0	13.5
General Cargo	9.4	15.9
Vehicles Carrier	8.6	14.5
Tanker	7.6	12.8
Other	10.5	17.7

Since MDTA had not performed a bridge risk assessment on the Key Bridge, nor did they have the ultimate lateral pier resistance capacities, the NTSB requested the Office of Bridges and Structures of the Federal Highway Administration (FHWA) to provide the NTSB with the lateral pier resistance capacities. The FHWA provided the following lateral pier capacities:[53]

Table 21. *Lateral Resistance of Pier 16, Pier 17, Pier 18, and Pier 19*

Pier	Lateral Load Capacity (kips)	Mode of Failure
16	1,908	Foundation H-pile
17	5,509 at elev. 28.5′ 6,877 at elev. 57.5′	Column base shear (interface), nonlinear response Column base moment, linear-elastic response
18	5,459 at elev. 28.5′ 7,019 at elev. 57.5′	Column base shear (interface), nonlinear response Column base moment, linear-elastic response
19	1,920	Foundation H-pile

As seen in **Table 21**, the lateral load capacity of Pier 17 and Pier 18 was dependent upon the elevation of the impact at the column. A conservative approach was taken to calculate PC by using the minimum lateral load capacities for Pier 17 (5,509 kips) and Pier 18 (5,459 kips).

The equivalent static ship impact force in kips, P_S, is a function of the DWT and ship impact speed in feet per second, V, and is calculated as follows:

$$P_S = 8.15V\sqrt{DWT}$$

The probability of collapse, PC, for Pier 16 for each vessel category based on DWT and average vessel speed was computed and is presented in **Table 22**.

Table 22. *Probability of Collapse for Pier 16*

Vessel ID	Vessel Type	DWT (tons)	V (fps)	H_P (kips)	P_S (kips)	H_p/P	PC
1	Container	4,887	7.4	1,908	4,212	0.453	0.0607
2	Bulk Carrier	7,690	6.2	1,908	4,432	0.430	0.0632
3	General Cargo	7,690	6.7	1,908	4,763	0.401	0.0665
4	Vehicles	4,887	5.8	1,908	3,284	0.581	0.0465
5	Tanker	5,775	2.0	1,908	1,246	1.531	0.0000
6	Other	1,000	10.9	1,908	2,797	0.682	0.0353
7	Other	3,000	8.5	1,908	3,811	0.501	0.0554
8	Other	5,000	10.7	1,908	6,155	0.310	0.0766
9	Other	7,690	10.9	1,908	7,777	0.245	0.0838

[53] See Bridge Protection Systems Attachment – FHWA FSK Bridge Main Span Pier Lateral Capacity.

The probability of collapse, PC, for Pier 17 for each vessel category based on DWT and average vessel speed was computed and is presented in **Table 23**.

Table 23. *Probability of Collapse for Pier 17*

Vessel ID	Vessel Type	DWT (tons)	V (fps)	H_P (kips)	P_S (kips)	H_p/P	PC
1	Container	5,000	12.6	5,509	7,279	0.757	0.0270
2	Container	15,000	12.9	5,509	12,851	0.429	0.0634
3	Container	25,000	12.8	5,509	16,514	0.334	0.0740
4	Container	35,000	12.9	5,509	19,608	0.281	0.0798
5	Container	45,000	12.9	5,509	22,227	0.248	0.0835
6	Container	55,000	13.0	5,509	24,887	0.221	0.0864
7	Container	65,000	12.9	5,509	26,897	0.205	0.0883
8	Container	75,000	13.0	5,509	28,963	0.190	0.0899
9	Container	85,000	13.0	5,509	30,895	0.178	0.0912
10	Container	95,000	13.1	5,509	32,910	0.167	0.0924
11	Container	105,000	13.1	5,509	34,661	0.159	0.0934
12	Bulk Carrier	5,000	12.0	5,509	6,917	0.796	0.0226
13	Bulk Carrier	15,000	12.4	5,509	12,371	0.445	0.0616
14	Bulk Carrier	25,000	11.7	5,509	15,107	0.365	0.0705
15	Bulk Carrier	35,000	12.2	5,509	18,588	0.296	0.0781
16	Bulk Carrier	45,000	12.4	5,509	21,433	0.257	0.0825
17	Bulk Carrier	55,000	12.6	5,509	23,998	0.230	0.0855
18	Bulk Carrier	65,000	12.5	5,509	25,936	0.212	0.0874
19	Bulk Carrier	75,000	12.5	5,509	27,929	0.197	0.0891
20	Bulk Carrier	85,000	12.5	5,509	29,791	0.185	0.0905
21	Bulk Carrier	95,000	12.7	5,509	31,792	0.173	0.0918
22	General Cargo	5,000	14.1	5,509	8,136	0.677	0.0358
23	General Cargo	15,000	14.4	5,509	14,386	0.383	0.0685
24	General Cargo	25,000	13.8	5,509	17,730	0.311	0.0765
25	General Cargo	35,000	13.8	5,509	20,974	0.263	0.0818
26	General Cargo	45,000	13.8	5,509	23,921	0.230	0.0854
27	General Cargo	55,000	13.8	5,509	26,367	0.209	0.0878
28	General Cargo	65,000	13.8	5,509	28,749	0.192	0.0897
29	Vehicles Carrier	5,000	12.6	5,509	7,243	0.761	0.0266
30	Vehicles Carrier	15,000	13.2	5,509	13,126	0.420	0.0644
31	Vehicles Carrier	25,000	12.7	5,509	16,380	0.336	0.0737
32	Vehicles Carrier	35,000	12.9	5,509	19,680	0.280	0.0799
33	Vehicles Carrier	45,000	13.1	5,509	22,681	0.243	0.0840
34	Tanker	5,000	10.9	5,509	6,307	0.873	0.0141
35	Tanker	15,000	11.7	5,509	11,644	0.473	0.0585
36	Tanker	25,000	10.9	5,509	14,029	0.393	0.0674
37	Tanker	35,000	11.0	5,509	16,734	0.329	0.0745
38	Tanker	45,000	11.3	5,509	19,476	0.283	0.0796

(*table continues*)

Vessel ID	Vessel Type	DWT (tons)	*V* (fps)	H_P (kips)	P_S (kips)	H_p/P	PC
39	Tanker	75,000	11.4	5,509	25,552	0.216	0.0871
40	Other	1,000	11.8	5,509	3,034	1.816	0.0000
41	Other	3,000	11.4	5,509	5,101	1.080	0.0000
42	Other	5,000	11.7	5,509	6,770	0.814	0.0207
43	Other	7,000	11.8	5,509	8,031	0.686	0.0349
44	Other	9,000	11.8	5,509	9,095	0.606	0.0438
45	Other	11,000	11.8	5,509	10,064	0.547	0.0502
46	Other	13,000	11.8	5,509	10,940	0.504	0.0551

The probability of collapse, PC, for Pier 18 for each vessel category based on DWT and average vessel speed was computed and is presented in **Table 24**.

Table 24. *Probability of Collapse for Pier 18*

Vessel ID	Vessel Type	DWT (ton)	*V* (fps)	H_P (kips)	P_S (kips)	H_p/P	PC
1	Container	5,000	12.6	5,459	7,279	0.750	0.0278
2	Container	15,000	12.9	5,459	12,851	0.425	0.0638
3	Container	25,000	12.8	5,459	16,514	0.331	0.0743
4	Container	35,000	12.9	5,459	19,608	0.278	0.0801
5	Container	45,000	12.9	5,459	22,227	0.246	0.0837
6	Container	55,000	13.0	5,459	24,887	0.219	0.0867
7	Container	65,000	12.9	5,459	26,897	0.203	0.0885
8	Container	75,000	13.0	5,459	28,963	0.188	0.0901
9	Container	85,000	13.0	5,459	30,895	0.177	0.0914
10	Container	95,000	13.1	5,459	32,910	0.166	0.0926
11	Container	105,000	13.1	5,459	34,661	0.157	0.0935
12	Bulk Carrier	5,000	12.0	5,459	6,917	0.789	0.0234
13	Bulk Carrier	15,000	12.4	5,459	12,371	0.441	0.0620
14	Bulk Carrier	25,000	11.7	5,459	15,107	0.361	0.0709
15	Bulk Carrier	35,000	12.2	5,459	18,588	0.294	0.0784
16	Bulk Carrier	45,000	12.4	5,459	21,433	0.255	0.0827
17	Bulk Carrier	55,000	12.6	5,459	23,998	0.227	0.0858
18	Bulk Carrier	65,000	12.5	5,459	25,936	0.210	0.0876
19	Bulk Carrier	75,000	12.5	5,459	27,929	0.195	0.0893
20	Bulk Carrier	85,000	12.5	5,459	29,791	0.183	0.0907
21	Bulk Carrier	95,000	12.7	5,459	31,792	0.172	0.0919
22	General Cargo	5,000	14.1	5,459	8,136	0.671	0.0365
23	General Cargo	15,000	14.4	5,459	14,386	0.379	0.0689
24	General Cargo	25,000	13.8	5,459	17,730	0.308	0.0768
25	General Cargo	35,000	13.8	5,459	20,974	0.260	0.0821
26	General Cargo	45,000	13.8	5,459	23,921	0.228	0.0857
27	General Cargo	55,000	13.8	5,459	26,367	0.207	0.0880
28	General Cargo	65,000	13.8	5,459	28,749	0.190	0.0899

(*table continues*)

Vessel ID	Vessel Type	DWT (ton)	*V* (fps)	H_P (kips)	P_S (kips)	H_p/P	PC
29	Vehicles Carrier	5,000	12.6	5,459	7,243	0.754	0.0273
30	Vehicles Carrier	15,000	13.2	5,459	13,126	0.416	0.0648
31	Vehicles Carrier	25,000	12.7	5,459	16,380	0.333	0.0740
32	Vehicles Carrier	35,000	12.9	5,459	19,680	0.277	0.0802
33	Vehicles Carrier	45,000	13.1	5,459	22,681	0.241	0.0843
34	Tanker	5,000	10.9	5,459	6,307	0.865	0.0149
35	Tanker	15,000	11.7	5,459	11,644	0.469	0.0590
36	Tanker	25,000	10.9	5,459	14,029	0.389	0.0678
37	Tanker	35,000	11.0	5,459	16,734	0.326	0.0748
38	Tanker	45,000	11.3	5,459	19,476	0.280	0.0799
39	Tanker	75,000	11.4	5,459	25,552	0.214	0.0873
40	Other	1,000	11.8	5,459	3,034	1.799	0.0000
41	Other	3,000	11.4	5,459	5,101	1.070	0.0000
42	Other	5,000	11.7	5,459	6,770	0.806	0.0215
43	Other	7,000	11.8	5,459	8,031	0.680	0.0356
44	Other	9,000	11.8	5,459	9,095	0.600	0.0444
45	Other	11,000	11.8	5,459	10,064	0.542	0.0508
46	Other	13,000	11.8	5,459	10,940	0.499	0.0556

The probability of collapse, PC, for Pier 19 for each vessel category based on DWT and average vessel speed was computed and is presented in **Table 25**.

Table 25. *Probability of Collapse for Pier 19*

Vessel ID	Vessel Type	DWT (ton)	*V* (fps)	H_P (kips)	P_S (kips)	H_p/P	PC
1	Bulk Carrier	1,935	5.4	1,920	1,953	0.983	0.0019
2	General Cargo	1,935	6.7	1,920	2,389	0.804	0.0218
3	Other	1,935	10.9	1,920	3,890	0.494	0.0562

4.5 Protection Factor (*PF*)

The purpose of the protection factor is to adjust the annual frequency of collapse for full or partial protection of selected bridge piers against vessel collisions due to protection measures (dolphins, islands, etc.), existing site conditions such as a parallel bridge protecting a bridge from impacts in one direction, a feature of the waterway (such as a peninsula extending out on one side of the bridge) that may block vessels from hitting bridge piers, or a wharf structure near the bridge that may block vessels from a certain direction.[54]

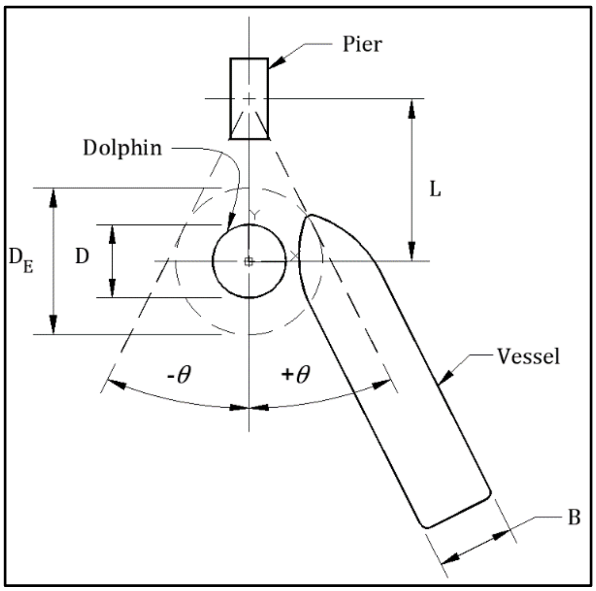
[54] See Section 4.8.3.5 – *Protection Factor* in AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges. 2nd Edition. Washington, DC, page 79.

The protection factor, PF, is computed as:

$$PF = 1 - \left(\frac{\%\text{Protection Provided}}{100}\right)$$

If no protection of the pier exists, then $PF = 1.0$. If the pier is 100 percent protected, then $PF = 0.0$. If the pier protection (for example, a dolphin system) provides 70 percent protection, then PF would be equal to 0.3.

The recommended procedure for estimating values for PF is illustrated in the model below developed to estimate the protection angle provided by a dolphin.



$D_E = D + 0.75B$

$\theta = \sin^{-1}\left[\frac{D_E}{2L}\right]$

Where:

D_E	=	Effective dolphin diameter (feet)
D	=	Diameter of dolphin (feet)
B	=	Beam (width) of vessel (feet)
θ	=	Protection angle provided by dolphin
L	=	Distance between center of dolphin and center of pier

Figure 53. Model to estimate the protection angle provided by a dolphin (source: AASHTO).

The percentage of protection provided is equivalent to the area under the normal distribution of vessel collision trajectories around a bridge pier, which is bounded on the left and right by the computed protection angle. The normal distribution has a standard deviation (σ) of 30 degrees and mean (μ) of 0 degrees (see **Figure 54**).

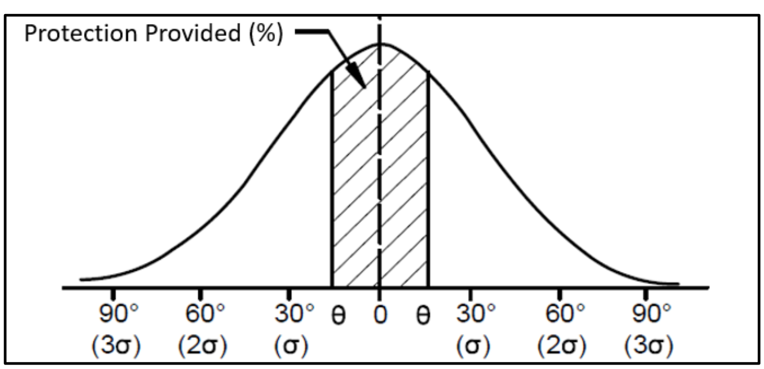


Figure 54. Normal distribution of vessel collision trajectories around a bridge pier (source: AASHTO)

Dolphin #1 and Dolphin #2 were 475 feet clear of the center of Pier 17 and Pier 18; therefore, when accounting for the 28-foot diameter cap, the dolphins were located 489 feet west of the centers of Pier 17 and Pier 18. Dolphin #3 and Dolphin #4 were 350 feet clear of the center of Pier 17 and Pier 18; therefore, when accounting for the 28-foot diameter cap, the dolphins were located 364 feet east of the centers of Pier 17 and Pier 18.

Table 26 depicts the values that were used in conjunction with the beam of each vessel type to compute the protection angle of each dolphin.

Table 26. *Dolphin Parameters*

Dolphin	Diameter (D)	Distance (L)
1	28.0 feet	489 feet
2	28.0 feet	489 feet
3	28.0 feet	364 feet
4	28.0 feet	364 feet

The computed protection angle represents the left and right bounds of the area under the normal distribution.

Next, the left and right bounds of the normal distribution, which had a standard deviation, σ, equivalent to 30 degrees, and a mean, μ, of 0 degrees, was utilized to calculate the corresponding z-scores as follows:

$$z_L = \frac{\theta_L - \mu}{\sigma} \qquad z_R = \frac{\theta_R - \mu}{\sigma}$$

The z-scores represent the area under the normal distribution curve to the left of the respective z-score. Therefore, the difference between the two areas represents the area under the normal distribution curve between the two z-score values. The percentage of protection, $P_{\%}$, provided by the dolphins was calculated for each vessel type as follows:

$$P_{\%} = z_R - z_L$$

Where: z_R = Area to the left of the positive z-score
z_L = Area to the left of the negative z-score

With the percentage of protection provided by each dolphin computed, the protection factor (PF) was calculated as follows:

$$PF = 1 - P_{\%}$$

Using Microsoft Excel, the protection factor, PF, for Pier 17 and Pier 18 for outbound vessels from each vessel category was computed and is presented in **Table 27**. Since Pier 16 and Pier 19 did not have pier protection, they had a PF of 1.0.

Table 27. *Protection Factor for Pier 17 and Pier 18 for Outbound Vessels*

Vessel ID	Vessel Type	B (ft)	D_E (ft)	θ (deg)	z_L	z_R	$P_{\%}$	PF
1	Container	110	111	6.49	-0.22	0.22	17.1%	0.8287
2	Container	148	139	8.15	-0.27	0.27	21.4%	0.7859
3	Container	122	120	7.03	-0.23	0.23	18.5%	0.8147
4	Container	125	121	7.13	-0.24	0.24	18.8%	0.8121
5	Container	126	123	7.20	-0.24	0.24	19.0%	0.8103
6	Container	147	138	8.14	-0.27	0.27	21.4%	0.7861
7	Container	130	125	7.37	-0.25	0.25	19.4%	0.8059
8	Container	139	132	7.77	-0.26	0.26	20.4%	0.7956
9	Container	141	134	7.88	-0.26	0.26	20.7%	0.7928
10	Container	143	135	7.94	-0.26	0.26	20.9%	0.7913
11	Container	145	137	8.03	-0.27	0.27	21.1%	0.7890
12	Bulk Carrier	106	108	6.33	-0.21	0.21	16.7%	0.8329
13	Bulk Carrier	145	137	8.04	-0.27	0.27	21.1%	0.7887
14	Bulk Carrier	99	102	5.99	-0.20	0.20	15.8%	0.8417
15	Bulk Carrier	122	119	7.01	-0.23	0.23	18.5%	0.8152
16	Bulk Carrier	126	123	7.20	-0.24	0.24	19.0%	0.8103
17	Bulk Carrier	147	138	8.14	-0.27	0.27	21.4%	0.7861
18	Bulk Carrier	130	125	7.37	-0.25	0.25	19.4%	0.8059
19	Bulk Carrier	139	132	7.77	-0.26	0.26	20.4%	0.7956
20	Bulk Carrier	141	134	7.88	-0.26	0.26	20.7%	0.7928
21	Bulk Carrier	145	137	8.03	-0.27	0.27	21.1%	0.7890
22	General Cargo	115	114	6.70	-0.22	0.22	17.7%	0.8233
23	General Cargo	136	130	7.65	-0.26	0.26	20.1%	0.7987
24	General Cargo	92	97	5.68	-0.19	0.19	15.0%	0.8498
25	General Cargo	98	101	5.94	-0.20	0.20	15.7%	0.8430
26	General Cargo	100	103	6.05	-0.20	0.20	16.0%	0.8402
27	General Cargo	105	107	6.27	-0.21	0.21	16.6%	0.8344
28	General Cargo	105	107	6.27	-0.21	0.21	16.6%	0.8344
29	Vehicles Carrier	103	105	6.18	-0.21	0.21	16.3%	0.8368
30	Vehicles Carrier	139	132	7.77	-0.26	0.26	20.4%	0.7956
31	Vehicles Carrier	107	108	6.35	-0.21	0.21	16.8%	0.8324
32	Vehicles Carrier	105	107	6.27	-0.21	0.21	16.6%	0.8344
33	Vehicles Carrier	106	108	6.31	-0.21	0.21	16.7%	0.8334
34	Tanker	102	105	6.14	-0.20	0.20	16.2%	0.8378
35	Tanker	137	130	7.66	-0.26	0.26	20.2%	0.7985
36	Tanker	121	119	6.99	-0.23	0.23	18.4%	0.8158
37	Tanker	103	105	6.19	-0.21	0.21	16.4%	0.8365

(*table continues*)

Vessel ID	Vessel Type	B (ft)	D_E (ft)	θ (deg)	z_L	z_R	$P_{\%}$	PF
38	Tanker	107	108	6.33	-0.21	0.21	16.7%	0.8329
39	Tanker	105	107	6.27	-0.21	0.21	16.6%	0.8344
40	Other	148	139	8.17	-0.27	0.27	21.5%	0.7854
41	Other	85	92	5.38	-0.18	0.18	14.2%	0.8577
42	Other	136	130	7.62	-0.25	0.25	20.1%	0.7995
43	Other	142	135	7.92	-0.26	0.26	20.8%	0.7918
44	Other	142	135	7.91	-0.26	0.26	20.8%	0.7920
45	Other	148	139	8.17	-0.27	0.27	21.5%	0.7854
46	Other	148	139	8.17	-0.27	0.27	21.5%	0.7854

The protection factor, PF, for Pier 17 and Pier 18 for inbound vessels from each vessel category was computed and is presented in **Table 28**.

Table 28. *Protection Factor for Pier 17 and Pier 18 for Inbound Vessels*

Vessel ID	Vessel Type	B (ft)	D_E (ft)	θ (deg)	z_L	z_R	$P_{\%}$	PF
1	Container	110	111	8.74	-0.29	0.29	22.9%	0.7708
2	Container	148	139	10.98	-0.37	0.37	28.6%	0.7144
3	Container	122	120	9.46	-0.32	0.32	24.8%	0.7525
4	Container	125	121	9.60	-0.32	0.32	25.1%	0.7490
5	Container	126	123	9.69	-0.32	0.32	25.3%	0.7467
6	Container	147	138	10.97	-0.37	0.37	28.5%	0.7146
7	Container	130	125	9.92	-0.33	0.33	25.9%	0.7409
8	Container	139	132	10.47	-0.35	0.35	27.3%	0.7271
9	Container	141	134	10.61	-0.35	0.35	27.6%	0.7236
10	Container	143	135	10.69	-0.36	0.36	27.8%	0.7216
11	Container	145	137	10.82	-0.36	0.36	28.2%	0.7183
12	Bulk Carrier	106	108	8.51	-0.28	0.28	22.3%	0.7767
13	Bulk Carrier	145	137	10.83	-0.36	0.36	28.2%	0.7181
14	Bulk Carrier	99	102	8.06	-0.27	0.27	21.2%	0.7882
15	Bulk Carrier	122	119	9.44	-0.31	0.31	24.7%	0.7530
16	Bulk Carrier	126	123	9.69	-0.32	0.32	25.3%	0.7467
17	Bulk Carrier	147	138	10.97	-0.37	0.37	28.5%	0.7146
18	Bulk Carrier	130	125	9.92	-0.33	0.33	25.9%	0.7409
19	Bulk Carrier	139	132	10.47	-0.35	0.35	27.3%	0.7271
20	Bulk Carrier	141	134	10.61	-0.35	0.35	27.6%	0.7236
21	Bulk Carrier	145	137	10.82	-0.36	0.36	28.2%	0.7183
22	General Cargo	115	114	9.02	-0.30	0.30	23.6%	0.7637
23	General Cargo	136	130	10.30	-0.34	0.34	26.9%	0.7313
24	General Cargo	92	97	7.64	-0.25	0.25	20.1%	0.7990
25	General Cargo	98	101	7.99	-0.27	0.27	21.0%	0.7900
26	General Cargo	100	103	8.13	-0.27	0.27	21.4%	0.7864

(*table continues*)

Vessel ID	Vessel Type	B (ft)	D_E (ft)	θ (deg)	z_L	z_R	$P_{\%}$	PF
27	General Cargo	105	107	8.43	-0.28	0.28	22.1%	0.7787
28	General Cargo	105	107	8.43	-0.28	0.28	22.1%	0.7787
29	Vehicles Carrier	103	105	8.31	-0.28	0.28	21.8%	0.7818
30	Vehicles Carrier	139	132	10.46	-0.35	0.35	27.3%	0.7273
31	Vehicles Carrier	107	108	8.54	-0.28	0.28	22.4%	0.7759
32	Vehicles Carrier	105	107	8.43	-0.28	0.28	22.1%	0.7787
33	Vehicles Carrier	106	108	8.49	-0.28	0.28	22.3%	0.7772
34	Tanker	102	105	8.26	-0.28	0.28	21.7%	0.7831
35	Tanker	137	130	10.32	-0.34	0.34	26.9%	0.7308
36	Tanker	121	119	9.41	-0.31	0.31	24.6%	0.7538
37	Tanker	103	105	8.32	-0.28	0.28	21.9%	0.7815
38	Tanker	107	108	8.52	-0.28	0.28	22.4%	0.7764
39	Tanker	105	107	8.43	-0.28	0.28	22.1%	0.7787
40	Other	148	139	11.01	-0.37	0.37	28.6%	0.7136
41	Other	85	92	7.24	-0.24	0.24	19.1%	0.8093
42	Other	136	130	10.27	-0.34	0.34	26.8%	0.7321
43	Other	142	135	10.67	-0.36	0.36	27.8%	0.7221
44	Other	142	135	10.66	-0.36	0.36	27.8%	0.7223
45	Other	148	139	11.01	-0.37	0.37	28.6%	0.7136
46	Other	148	139	11.01	-0.37	0.37	28.6%	0.7136

4.6 Annual Frequency of Collapse Computation Results

The annual frequency of collapse (AF) was computed for each analyzed bridge element, Pier 16, Pier 17, Pier 18, and Pier 19, the piers likely to be struck be an aberrant ocean-going vessel transiting the main navigational channel. This was accomplished by computing the AF of each vessel category and summing the computed AF values for each pier. Finally, the summation of AF of each pier was equivalent to the AF for the entire bridge structure.

The AASHTO acceptable annual frequency of collapse of critical/essential bridges is 0.0001. Computations performed to calculate the annual frequency of collapse of the Key Bridge, based upon ocean-going vessel traffic from 2023, waterway characteristics, and bridge characteristics, including the ultimate lateral capacities of Pier 16, Pier 17, Pier 18, and Pier 19, determined the annual frequency of collapse was 0.002921 (see **Table 29)**.[55]

[55] See Bridge Protection Systems Attachment – Annual Frequency of Collapse (AF) Computations.

Table 29. *Annual Frequency of Collapse Summary*

Pier	Annual Frequency of Collapse		
	Inbound	**Outbound**	**Total**
16	0.000024	0.000024	0.000048
17	0.000687	0.000743	0.001430
18	0.000693	0.000749	0.001442
19	0.000001	0.000000	0.000001
Total	0.001405	0.001516	0.002921

When compared to the AASHTO acceptable annual frequency of collapse for a bridge designed in accordance with requirements after 1991, the calculated annual frequency of collapse for the Key Bridge was 29 times greater than the AASHTO acceptable annual frequency of collapse of new critical/essential bridges.

H. CONSTRUCTION ACTIVITIES

At the time of the bridge collapse, Brawner Builders, Inc., a prime contractor for the MDTA, had employees on the bridge repairing concrete spalling under contract MR-3025-0000, Task Order #2951. Spalling concrete refers to the phenomenon of surface patches of concrete breaking up and delaminating in the absence of immediate external influences associated with the expansion of reinforcing steel as it corrodes in the presence of chlorides (usually from road salts).

Personnel on the bridge at the time of the collapse included seven employees from Brawner Builders, Inc. and one employee, an inspector, from Eborn Enterprises, Inc., a subconsultant to the MDTA. All personnel were within the southbound right lane, which was closed to vehicular traffic using orange traffic cones. In addition to the personnel on the bridge, there were several construction vehicles and various construction equipment stationary within the closed right lane.[56] The bridge was open for vehicular traffic in both directions with the right southbound lane closed.

A video, recorded by a forward-facing camera inside a tractor-trailer combination vehicle, was obtained by NTSB investigators. The combination vehicle, which was traveling south on MD 695, crossed the North Abutment of the bridge at approximately 1:25:46 a.m., and departed the south end of the bridge at 1:27:35 a.m., approximately less than two minutes before the collapse of the bridge. The video recorded the lane closure (began 0.4 mile north of the North Abutment and ended 0.6 mile north of the South Abutment), positions of the construction vehicles, equipment, and the Eborn Enterprises, Inc. inspector prior to the collapse of the bridge (see **Figure 55** through **Figure 62**).

[56] See Bridge Protection Systems Attachment – Construction Vehicles Location Plan.

Figure 55. A passenger vehicle and Eborn Enterprises inspector (middle Span 22).

Figure 56. A stake bed truck with crash attenuator and light board (north end Span 20).

Figure 57. A pickup truck towing a light tower (south end Span 20).

Figure 58. a stake bed truck carrying orange traffic cones (north end Span 18).

Figure 59. a dump truck towing a concrete mixer (north end Span 18).

Figure 60. A dump truck towing a generator (north end Span 18).

Figure 61. A pickup truck towing a generator (north Span 18).

Figure 62. The last traffic cone for the lane closure (middle Span 17).

I. EMERGENCY CLOSURE OF THE FSK BRIDGE

At 01:27:01 a.m., the MDTA Police Duty Officer (MDTA DO) received a telephone call from the pilot dispatcher advising the duty officer of the vessel's situation.

At 01:27:53 a.m., the MDTA DO broadcasted "I need one of you guys on the south side, one of you guys on the north side to hold all traffic on the Key Bridge. There's a ship approaching that just lost their steering so until they get that under control, we gotta stop all traffic" to MDTA Police officers that had already been positioned at each end of the bridge for the construction activities.

At 01:28:22 a.m., both ends of the Key Bridge were closed to traffic by the MDTA Police officers.

At 01:29:27 a.m., MDTA Police Unit C13 broadcasted "C13 to Dispatch, the whole bridge just fell down. The whole bridge just collapsed" to the MDTA DO.

J. PREVIOUS VESSEL COLLISION WITH THE KEY BRIDGE

On August 29, 1980, the *Blue Nagoya*, a Roll-on/Roll-off (Ro-ro) Cargo vessel with a DWT of 7,613 tons, was sailing at 12 knots when it lost all propulsion and control about 600 yards from the bridge. The vessel drifted into Pier 17 at a speed of about 6 knots and ended up wedged in between the inverted V-configuration of Pier 17 destroying the fendering system. The pilot of the vessel was able to backout, free the bow, and proceed to a nearby anchorage. The conditions at the time were haze and visibility of 2 miles. In 1981, the Pier 17 fendering system was rebuilt to original specifications under Contract No. BRB 4-722.

On July 15, 2024, The NTSB interviewed a retired United States Coast Guard (USCG) Captain who participated in the investigation of the *Blue Nagoya* collision. The captain said the cause of the 1980 collision was determined to be an expansion tank overflowing onto and shorting of the main electrical control board, which resulted in a total loss of power and control. During the interview, the captain stated that Pier 17 was inspected, and he recalled the MDTA observed a scrape mark on one of the columns of the pier.

K. PROTECTION SYSTEMS ON OTHER BRIDGES OWNED BY THE MDTA

The protection systems (or lack thereof) on other bridges owned and operated by the MDTA include the following:

- <u>Thomas J. Hatem Memorial Bridge (US-40 in Havre de Grace and Perryville)</u> - no specific protection systems were included in the original construction of the bridge. There are no dolphins present.

- William Preston Lane Jr. Memorial (Bay) Bridge (US-50/US-301 in Anne Arundel and Queen Anne's Counties) - The main navigational channel piers of the bridge include combined timber/steel fender systems around the circumference of the piers. The anchor piers do not have a fender system; however, there are islands surrounding the anchor piers for the south bridge. There are no dolphins present.

  The MDTA is evaluating the feasibility of long-term physical protection systems to the Bay Bridge that include rock islands, pier protections systems, and dolphins. The MDTA is working with the USCG and other stakeholders to determine if there are changes to maritime regulations that can be employed such as possibly a regulated navigational area. The MDTA confirmed in an email they have not conducted the AASHTO Method II calculations in the past on the Bay Bridge.[57]

- Governor Harry W. Nice Memorial Bridge (US-301 in Newburg and Dahlgren, Virginia) – a protection system at the bridge was constructed as part of the bridge replacement project. It includes precast concrete protection supported on steel pipe piles that surround main channel piers. There are no dolphins present.

L. NTSB INTERVIEWS

A total of six interviews of staff with the MDTA, Eborn Enterprises, Inc., and the United States Coast Guard were conducted (see **Table 30**).[58] A copy of the interview transcriptions for each interview can be found in the NTSB public docket for this investigation.

Table 30: *Summary of NTSB Interviews.*

Title	Organization	Date
Director of Construction	MDTA	April 24, 2024
Structures Engineering Manager	MDTA	April 24, 2024
Bridge Inspector	Eborn Enterprises, Inc.	May 9, 2024
Retired Captain	United States Coast Guard	July 15, 2024
Lieutenant Commander, Division Chief for Sector Maryland, National Capitol Region	United States Coast Guard	August 7, 2024
Fifth District Bridge Manager	United States Coast Guard	August 14, 2024

[57] See Bridge Protection Systems Attachment – Email from MDTA dated October 2, 2024.
[58] See the Bridge Protection Systems attachments for interview transcripts.

M. PREVIOUS BRIDGE COLLAPSES INVESTIGATED BY THE NTSB

1.0 Sunshine Skyway Bridge Collapse in Tampa Bay, Florida

The NTSB investigated a bridge collapse on May 9, 1980, in which a Liberian bulk carrier *Summit Venture* collided with a support pier of the western span of the Sunshine Skyway Bridge in Tampa Bay, Florida.

The NTSB determined the probable cause was "the *Summit Venture's* unexpected encounter with severe weather involving high winds and heavy rain associated with a line of intense thunderstorms which overtook the vessel as it approached the Sunshine Skyway Bridge, the failure of the National Weather Service to issue a severe weather warning for mariners, and the failure of the pilot to abandon the transit when visual and radar navigational references for the channel and the bridge were lost in the heavy rain. Contributing to the loss of life and to the extensive damage was the lack of structural pier protection systems which could have absorbed some of the impact force or redirected the vessel. Contributing to the loss of life was the lack of a motorist warning system which could have warned the highway vehicle drivers of the danger ahead."

As a result of the collision, the support pier was destroyed and about 1,297 feet of bridge deck and superstructure fell from a height of about 150 feet into the bay. A Greyhound bus, a small pickup truck, and six automobiles fell into the bay and 35 persons died. Repair costs were estimated at about $30 million for the bridge and about $1 million for the *Summit Venture*.

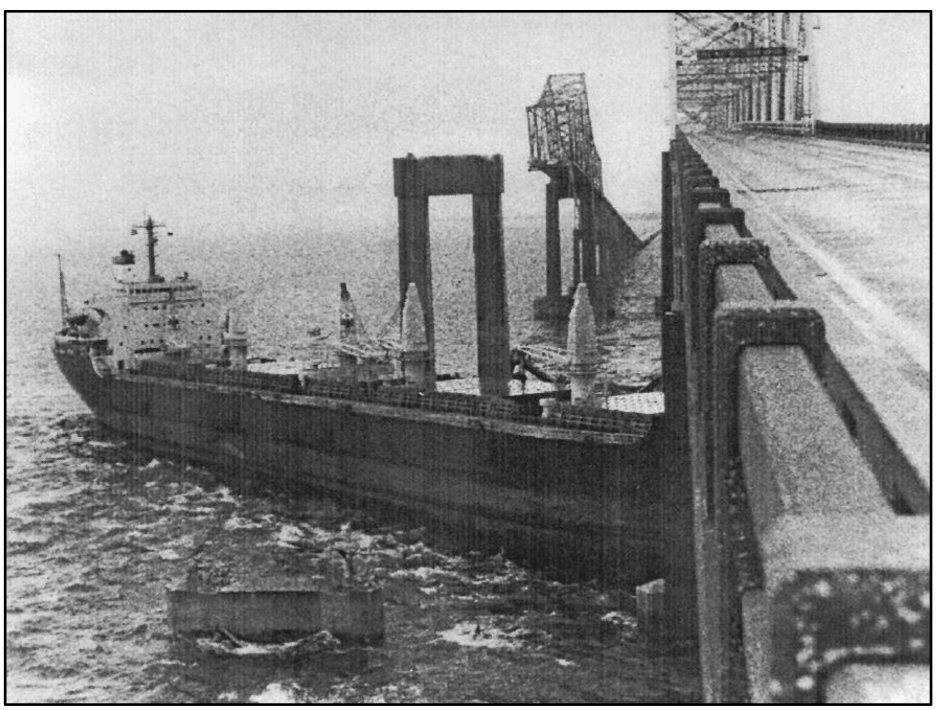


Figure 63: View of the collapsed western span of the Sunshine Skyway Bridge looking to the north.

Following the collapse, the new protection system for the Sunshine Skyway Bridge included the following taken from the 2009 AASHTO *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges,* 2nd Edition:[59]

> *"The Sunshine Skyway Bridge pier protection system developed by Greiner, Inc. for the Florida Department of Transportation utilizes a combination of dolphin and island protection as shown in* (see **Figure 64**) *(Greiner, 1985). The main piers are protected by islands whereas the five approach piers on each side of the main piers are protected by a dolphin system. The use of dolphins to protect the high-level approach piers was a result of the risk analysis which indicated that the high-level approach piers were vulnerable to a catastrophic vessel collision. The 60-feet diameter cells were designed to withstand a collision from either a loaded 23,000-DWT* [deadweight tonnage] *or an empty 87,300-DWT bulk carrier; the 54 feet-by– 4 inch-diameter dolphins from impacts with a loaded 25,000-DWT barge, or an empty 70,000-DWT vessel; and the 47-foot-diameter cells to withstand impacts from a loaded 15,000-DWT barge or an empty 35,000-DWT ship. All design impact speeds were 10 knots. The Skyway sheet piling was driven through a sand overburden (10 – 40 feet thick) and then 5 to 10 feet into a stiff limestone stratum known as the Hawthorne Formation."*

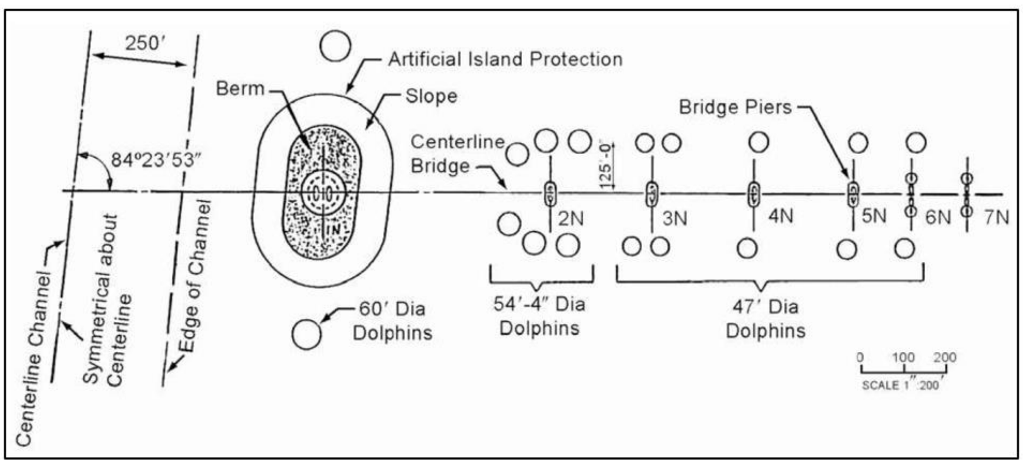


Figure 64: Dolphin and Island Protection System Plan for the Sunshine Skyway Bridge, Tampa Bay, FL (source: AASHTO).

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[59] See Section 7.3.3 - *Dolphin Protection* in AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges. 2nd Edition. Washington, DC, pages 119 and 120.

Figure 65 illustrates an aerial view of the new protection systems for the Sunshine Skyway Bridge in Tampa Bay, FL, after the collapse.

Figure 65: Aerial view of the new pier protection system for the Sunshine Skyway Bridge in Tampa Bay, FL, after the collapse (source: FDOT).

2.0 Queen Isabella Causeway Bridge Collapse near South Padre Island, Texas

The NTSB investigated a bridge collapse on September 15, 2001, in which the towboat *Brown Water V*, pushing four barges collided with the Queen Isabella Causeway, which connects South Padre Island to the mainland in Cameron County, Texas.

The collision caused two sections of the causeway (approximately 160 feet long and 85 feet above the water) to collapse. Ten passenger vehicles either fell with the collapsing sections or drove off the end of the remaining structure of the roadway resulting in eight fatalities. A third adjacent section of the causeway collapsed later that day in the afternoon.

The barges were drafting[60] approximately 9 feet of water at the time of the accident and were outside of the main shipping channel by about 175 yards. The winds in the area were strong and effects from a recent tropical depression on the day of the accident had resulted in a flood tide.

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[60] The distance is measured from the waterline to the bottom of the vessel.

The accident closed the 2.37-mile-long bridge, which was the only vehicular span linking the mainland to South Padre Island. More than 19,000 vehicles per day typically traveled the causeway. The Queen Isabella Causeway was constructed in the early 1970's.

Figure 66: View of the main shipping channel and collapsed portion of the Queen Isabella Causeway looking to the north.

Figure 67: View of the collapsed Queen Isabella Causeway bridge bent and adjacent undamaged bents looking to the northeast.

Following the collapse, the Texas Department of Transportation (TxDOT) installed an early warning collapse detection system on the Queen Isabella Causeway bridge in 2005 that included the following:

- Installation of beacons in each direction of travel spaced at 560 feet.
- Installation of gate arms at both ends of the bridge preventing vehicular traffic from entering the bridge.
- Signage in each direction of travel indicating *"Stop When Flashing DANGER."*
- Installation of fiber optic cable to connect the beacons.
- Installation of a control box in which the system is tested annually.

Figure 68 is a view of the early warning collapse detection system on the Queen Isabella Causeway bridge with beacons spaced at 560 feet looking to the east.

Figure 68: Early warning collapse detection system on the Queen Isabella Causeway bridge (source: TxDOT).

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Figure 69 is a view of the gate arm and signage indicating *"Stop When Flashing DANGER"* on the Queen Isabella Causeway bridge looking to the east.

Figure 69: Gate arm and signage on the Queen Isabella Causeway bridge (source: TxDOT).

Figure 70 is a view of the collapsed portion of the Queen Isabella Causeway looking to the southeast illustrating no dolphins existed to protect the bridge bents at the highest sections of the causeway.

Figure 70: Collapsed portion of the Queen Isabella Causeway (source: TxDOT).

Figure 71 illustrates the new pier protection system for the Queen Isabella Causeway that consisted of 16-feet by 16-feet square pile cluster dolphins that protect the bridge bents at the highest sections of the causeway looking to the northwest.

Figure 71: New pier protection system for the Queen Isabella Causeway (source: TxDOT).

Figure 72 illustrates another view of the new pier protection system for the Queen Isabella Causeway that consisted of 16-feet by 16-feet square pile cluster dolphins that protect the bridge bents at the highest sections of the causeway looking to the west.

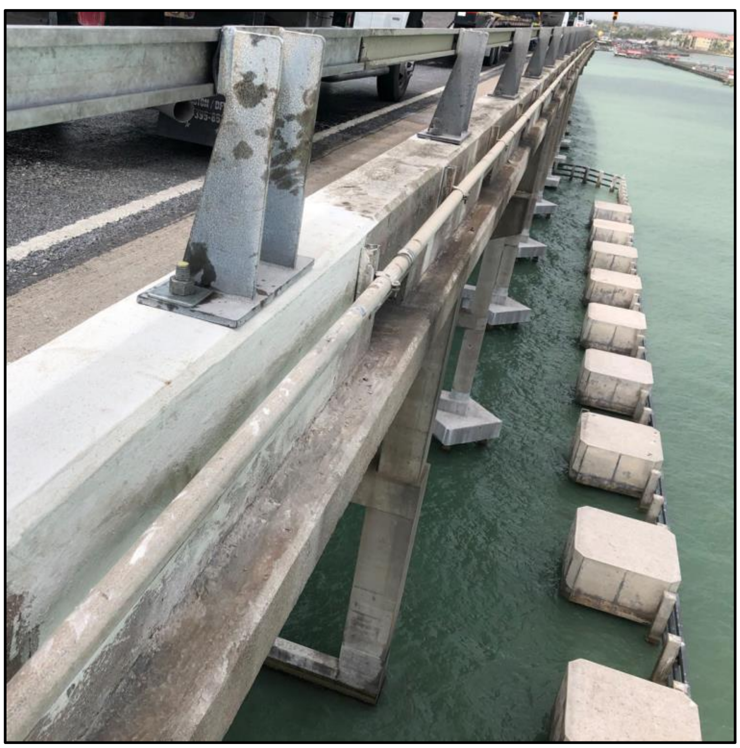

Figure 72: New pier protection system for the Queen Isabella Causeway (source: TxDOT).

3.0 I-40 Bridge Collapse near Webbers Falls, Oklahoma

The NTSB investigated a bridge collapse on May 26, 2002, in which the towboat *Robert Y. Love*, pushing two empty asphalt tank barges, was traveling northbound on the McClellan-Kerr Arkansas River Navigation System, near Webbers Falls, Oklahoma. As the tow approached the Interstate 40 (I-40) highway bridge at mile 360.3, it veered off course and collided with a pier 201 feet west of (outside) the navigation channel.

The NTSB determined that the probable cause of the Robert Y. Love's allision with the Interstate 40 highway bridge and its subsequent collapse was "the captain's loss of consciousness, possibly as the result of an unforeseeable abnormal heart rhythm. Contributing to the loss of life was the inability of motorists to detect the collapsed bridge in time to stop their vehicles."

The impact collapsed a 503-foot section of the bridge, which fell into the river and onto the barges below. According to witnesses, highway traffic continued to drive into the void in the bridge created by the collapsed spans. When traffic stopped, eight passenger vehicles and three truck tractor-semitrailer combinations had fallen into the river or onto the collapsed portions of the bridge. The accident resulted in 14 fatalities and 5 injuries and caused an estimated $30.1 million in damage to the bridge, including the operation of detours, and $276,000 in damage to the barges.

Figure 73 is a view of the collapsed portion of the I-40 bridge downstream from the approach to the bridge illustrating the navigation channel looking to the northwest.

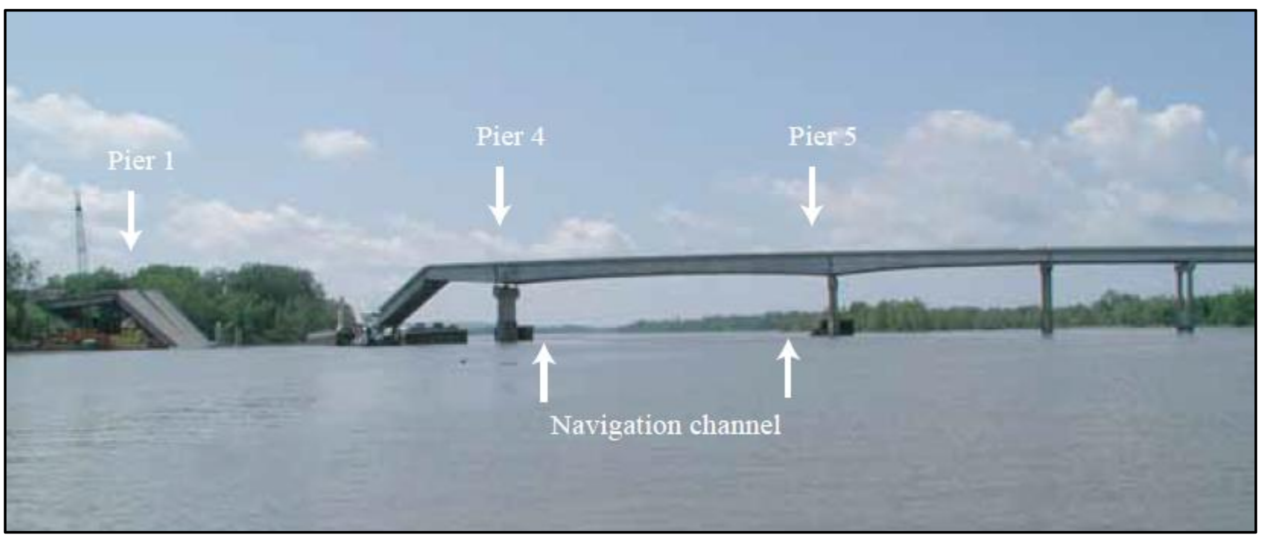

Figure 73: Collapsed portion of the I-40 bridge.

Figure 74 is a view of the collapsed portion of the I-40 bridge illustrating the 40 feet diameter dolphins protecting the piers of the navigational channel upstream of the bridge and the collapsed section resting on the barges downstream of the bridge looking to the north.

Figure 74: Collapsed portion of the I-40 bridge illustrating dolphins protecting the piers.

Figure 75 is an aerial view of the new pier protection system for the I-40 bridge that consists of 12-feet-diameter dolphins that protected almost every pier on the upstream and downstream side of the bridge except for the existing 40 feet diameter dolphins that protected the piers of the navigational channel upstream of the bridge looking to the southeast.

Figure 75: Aerial view of the new pier protection system for the I-40 bridge (source: Oklahoma Department of Transportation).

N. NEW PHYSICAL PROTECTION SYSTEM FOR THE DELAWARE MEMORIAL BRIDGE

The Delaware Memorial Bridge located near Wilmington, Delaware, was owned and operated by the Delaware River and Bay Authority (DRBA). **Figure 76** illustrates a view of the Delaware Memorial Bridge looking to the southeast prior to the construction of additional protections systems.

Figure 76: View of the Delaware Memorial Bridge looking to the southeast (source: Modjeski and Masters, Inc.).

Figure 77 illustrates views of the protection systems for the Delaware Memorial Bridge which consisted of a timber and steel fender system around the pier that did not contain dolphins. The fender systems were supported by the piers and was not an independently supported system.

Figure 77: Views of the protection systems for the Delaware Memorial Bridge (source: Modjeski and Masters, Inc.).

In 2019, due to previous accidents with the bridge, the DRBA performed studies to determine the required protection requirements and protection methods. These studies recommended that a separate protection system be installed to protect the bridge. The new protection system consisted of eight (8) 80-feet-diameter steel sheet pile cell dolphins. The dolphins were to be filled with rock and topped with a concrete cap. The cost was approximately $90 to $100 million to construct the eight dolphins, and two of the eight planned dolphins are currently completed.[61]

Figure 78 and **Figure 79** depict the new 80-feet-diameter dolphins added to the protection system for the Delaware Memorial Bridge

Figure 78: Four of the proposed eight new dolphins added to the protection system for the Delaware Memorial Bridge (source: Modjeski and Masters, Inc.).

Figure 79: Proposed eight new dolphins added to the protection system for the Delaware Memorial Bridge (source: Modjeski and Masters, Inc.).

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[61] It should be noted that this section does not imply appropriate protection measures and costs from one bridge directly transfers to another. Each bridge has its own conditions that affect design of appropriate protection systems.

O. OTHER BRIDGES FREQUENTED BY OCEAN-GOING VESSELS

The NTSB requested the Federal Highway Administration (FHWA) to identify bridges crossing waterways frequented by ocean-going or sea-faring vessels and to gather pertinent information on navigation protection devices at those bridges. The FHWA identified a total of 176 bridges in 26 states.[62] Of the 176 identified bridges, 115 of them had pier protection, 24 of them had substructures that were on land, and 37 of them did not have pier protection (see **Table 31**).

Table 31. *Protection Devices at the 152 Bridges that Have Piers in Water*

Pier Protection	Number of Bridges
Dolphins only	10 [7%]
Fenders only	61 [40%]
Islands only	9 [6%]
Dolphins and fenders	30 [20%]
Dolphins and islands	1 [1%]
Fenders and islands	2 [1%]
Dolphins, fenders, and islands	2 [1%]
No Pier Protection	37 [24%]

FHWA's efforts were based on input from State DOTs and did not consider vertical clearance of the bridge, nor did they establish a lower bound on the number of transits required to be considered "frequented." The NTSB established criteria for vertical clearance of the bridge that would accommodate ocean-going vessels and a minimum number of average annual transits of ocean-going vessels that would be considered "frequented." Along with the work performed by the FHWA, the NTSB identified additional bridges owned by the U.S. Army Corps of Engineers that were not included in FHWA's list of bridges. Ultimately, there were 72 bridges in 19 states crossing waterways frequented by ocean-going vessels. Four of the identified bridges met the NTSB filtering criteria; however, the respective bridge owners have conducted recent studies using current AASHTO standards and improvement projects are underway or scheduled to be completed by 2030.[63] Ultimately, the NTSB identified 68 bridges in 19 states crossing waterways frequented by ocean-going vessels.[64]

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[62] See Bridge Protection Systems Attachment – FHWA Bridges Crossing Waterways Utilized by Ocean-Going Vessels.

[63] The four bridges were the Oakland-San Francisco Bay Bridge (West Span), Delaware Memorial Bridge (eastbound and westbound), and the Blatnik Bridge.

[64] See Bridge Protection Systems Attachment – NTSB Critical/Essential and Typical Bridges Frequented by Ocean-Going Vessels.

P. DOCKET MATERIAL

The following attachments are included in the docket for this investigation:

1. Bridge Protection Systems Attachment – MDTA 2023 Main BIN Biennial Inspection Report
2. Bridge Protection Systems Attachment – NTSB Horizontal and Vertical Alignments
3. Bridge Protection Systems Attachment – Baltimore Harbor Outer Crossings Patapsco River Bridge As-Built Plans
4. Bridge Protection Systems Attachment – FSK Post-Collapse Damage
5. Bridge Protection Systems Attachment – MDTA 2023 Bridge Inspection Report (S17-S19)
6. Bridge Protection Systems Attachment – MDTA 2021 Underwater Inspection Report
7. Bridge Protection Systems Attachment – 2024 SIA for the FSK Bridge
8. Bridge Protection Systems Attachment – NTSB-Generated Nonredundant Steel Tension Member Plan
9. Bridge Protection Systems Attachment – Email from MDTA dated June 13, 2024
10. Bridge Protection Systems Attachment – FHWA Bridges Crossing Waterways Utilized by Ocean-Going Vessels
11. Bridge Protection Systems Attachment – NTSB Critical/Essential and Typical Bridges Frequented by Ocean-Going Vessels
12. Bridge Protection Systems Attachment – FHWA FSK Bridge Main Span Pier Lateral Capacity
13. Bridge Protection Systems Attachment – Annual Frequency of Collapse (AF) Computations
14. Bridge Protection Systems Attachment – Construction Vehicles Location Plan
15. Bridge Protection Systems Attachment – Email from MDTA dated October 2, 2024
16. Bridge Protection Systems Attachment – Interview Transcript of MDTA Director of Construction

17. Bridge Protection Systems Attachment – Interview Transcript of MDTA Structures Engineering Manager
18. Bridge Protection Systems Attachment – Interview Transcript of Eborn Enterprises Bridge Inspector
19. Bridge Protection Systems Attachment – Interview Transcript of Retired USCG Captain
20. Bridge Protection Systems Attachment – Interview Transcript of USCG LCDR
21. Bridge Protection Systems Attachment – Interview Transcript of USCG Fifth District Bridge Manager

Submitted by:

Dan Walsh, Co-Chair
Highway Factors Investigator

Scott Parent, Co-Chair
Highway Factors Investigator