Structural Assessment, Analysis, and Rehabilitation of a Masonry Aqueduct

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To avoid future arch collapse, engineers had to determine the failure mechanism of this Maryland aqueduct.

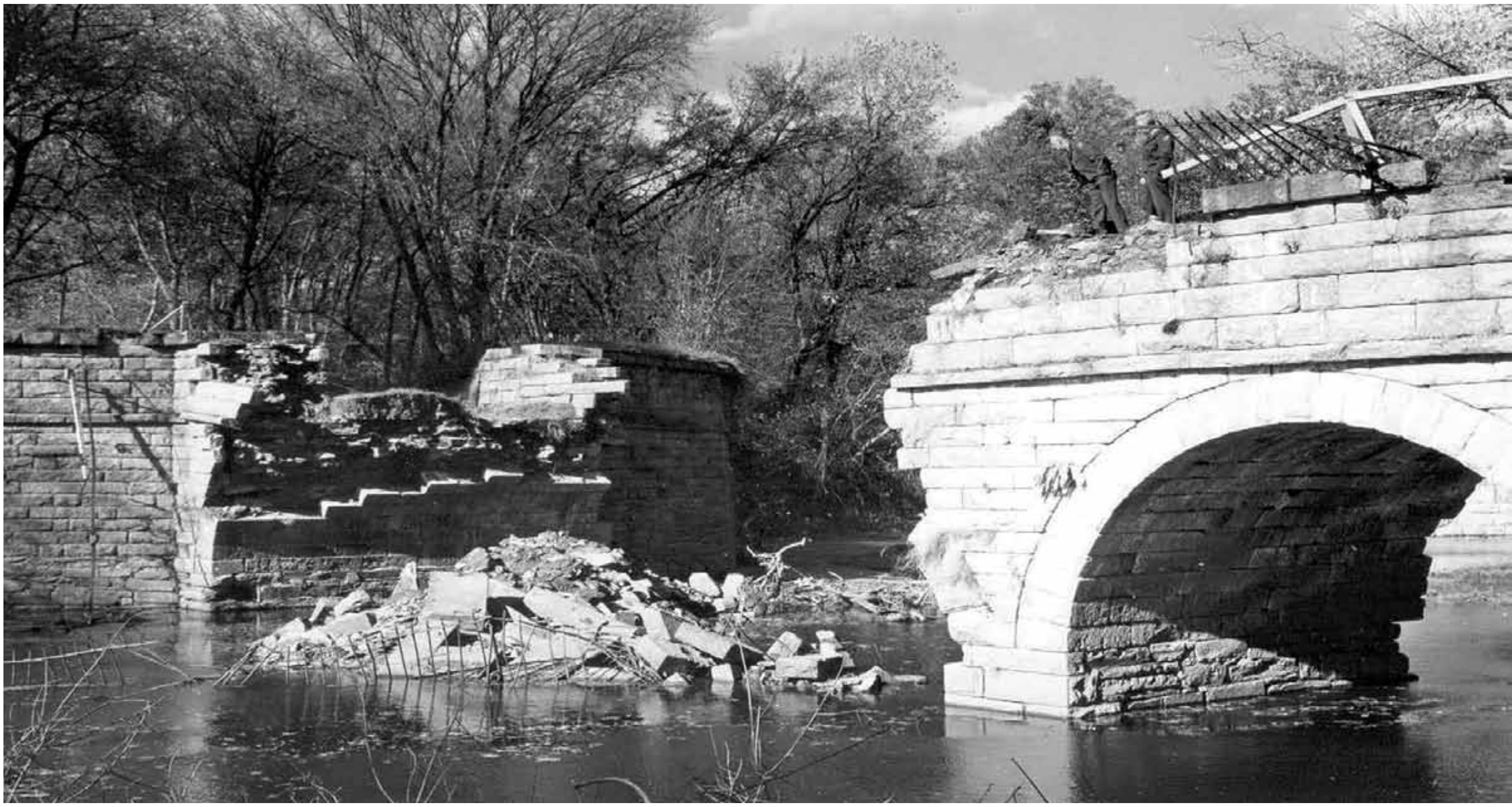


Fig. 1. Catoctin aqueduct, Lander, Maryland, collapsed center and western arches, 1973. The berm parapet and upstream spandrel wall had failed earlier. Note the railings bent in downstream direction, indicating predominate flood effects coming from tributaries and not the adjacent Potomac River. Courtesy of the C&O Canal National Historical Park Archives.

The failure of stone masonry arches has been studied extensively but mainly for the development of analytical modeling methods for bridges carrying vehicles.[1] This paper studies the collapse of a stone masonry arch aqueduct that carried boats across Catoctin Creek on the Chesapeake and Ohio (C&O) Canal near Lander, Maryland (Fig. 1). Among the inherent design flaws were the deterioration of the waterproofing system and the arrangement of unequal arch spans, both of which contributed to the collapse. The reconstruction of the aqueduct included reusing existing stones and developing methods for measuring and accurately locating the recovered ring stones in the arches. Similar substantially intact aqueducts of the same period on the C&O Canal, as well as aqueducts on other canals, were studied to understand the historic building techniques, deterioration from environmental effects, and causes of structural distress that can occur in these structures.

Background

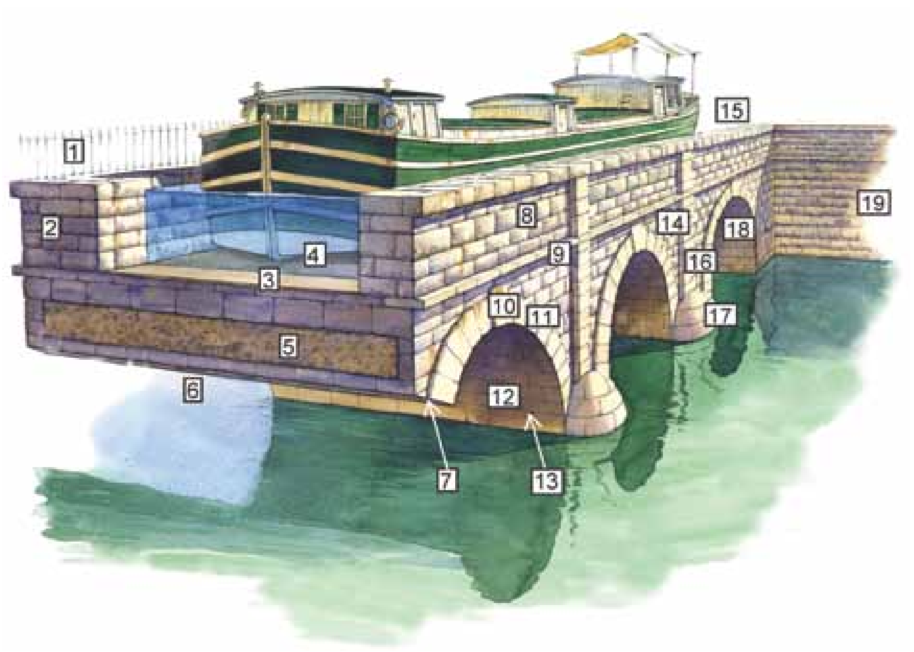
Aqueducts were first used to transport water for drinking, bathing, and irrigation. The Canal du Midi in France, built between 1666 and 1681, is one of the first European aqueducts used for navigation.[2] Navigation aqueducts are essentially bridges that carry water-filled canals instead of roads. Figure 2 is an artist's rendering of a C&O Canal aqueduct with notes identifying features and components. The rendering contains some inaccuracies (the most significant being that it shows the trunk floor as a full stone layer across the aqueduct, which does not exist on any excavated aqueducts). In general, though, the drawing gives a very good illustration of a typical aqueduct on the C&O Canal.

Construction of the C&O Canal began in 1828 in Little Falls, Maryland, just outside of the District of Columbia, and included 11 stone aqueducts designed to carry the canal and boats across the major river tributaries that drain into the Potomac River along the canal's route.[3] The canal depended on the Potomac for its water supply, which was both an advantage and a liability since the river is prone to severe and frequent flooding; between 1828 and 1996 the canal was flooded 144 times.[4] The need to keep the level of the canal close to the level of the river and to keep the river tributaries navigable required careful attention to canal elevations.

Now a park operated by the National Park Service, the C&O Canal extends 184.5 miles from Georgetown in Washington, D.C., to Cumberland, Maryland[5]; in many places the park is only a few hundred yards wide. The canal operated as a commercial transportation artery until 1924. The owner at that time, the Baltimore and Ohio (B&O) Railroad, had no interest in continuing operations. Ownership was transferred to the U.S. government in 1938. The canal came under the jurisdiction of the National Park Service when the Chesapeake and Ohio Canal National Historical Park was created in 1971.[6]

The Catoctin aqueduct was constructed between 1832 and 1834.[7] It was designed by Thomas F. Purcell, constructed by Tracey and Douglas Contractors, and was the third aqueduct constructed along the canal after the Seneca and the Monocacy aqueducts.[8]

Fig. 2. Typical cross section for aqueducts on the C&O Canal: 1. Railing. 2. Towpath parapet. 3. Trunk floor. 4. Trunk of aqueduct. 5. Rubble fill. 6. Arch barrel. 7. Extrados of arch. 8. Berm parapet. 9. Water table. 10. Keystone. 11. Ring stones. 12. Pier. 13. Spring line. 14. Spandrel wall. 15. Coping stones. 16. Pilaster. 17. Bullnose. 18. Abutment. 19. Wing wall. Courtesy of C&O Canal National Historical Park.



When the Catoctin aqueduct collapsed on October 30, 1973, the highly popular towpath was also severed, and the section from Mile Post 50.9 at Lock 29 to Mile Post 55.0 at Lock 30, a distance of four miles, was closed. Park users were forced to make an eight-mile detour along county roads. In 1974 a precast concrete pedestrian bridge was installed by the John Driggs Company over the creek adjacent to the remains of the aqueduct.[9] This bridge lasted only until October 1976, when it was destroyed in a flood. A Bailey bridge spanning the abutments of the aqueduct was installed in 1980 but at the expense of introducing a visually intrusive element into a natural and historically sensitive environment.[10]

Description of the Aqueduct

The Catoctin aqueduct is 130 feet long and 33 feet wide and has a waterway width of 20 to 21 feet. It is comprised of three arches: one central elliptical arch spanning 40 feet, flanked by two semi-circular arches, each spanning 20 feet.[11] In plan the aqueduct stood at an angle to the canal, such that the canal curved sharply into each end. This arrangement gave it the nickname of "crooked aqueduct."[12] It was an impressive, elegant structure with shallow arches and excellent ashlar-faced stonework. The ring stones, which have a raised rock-face finish surrounded by a narrow, flat margin, vary in height, with the maximum at the spring line and

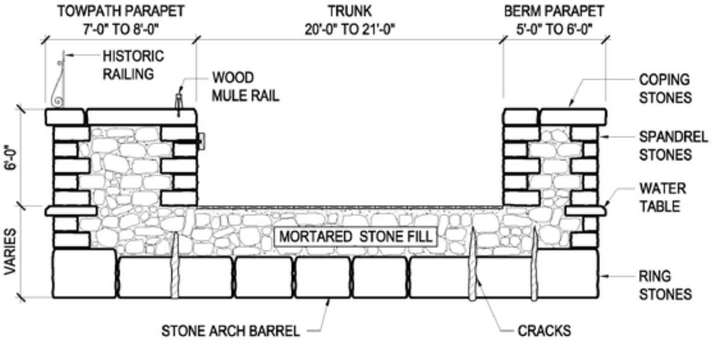


Fig. 3. Typical C&O Canal aqueduct cross section. Drawing by Denis McMullan.

tapering to a minimum at the apex of the arch. The graceful appearance of the aqueduct also resulted from the minimal vertical dimensions from the bottom of the water trunk to the top of the arches and to the low rise-to-span ratio of the central elliptical arch.

The arches were supported on stone piers and abutments. The solid cut stone in the piers stopped at the intersection of the extrados of the arches. Above the arches and inside the interior spandrel walls the aqueduct was filled with lower quality stone of varying sizes, commonly referred to as rubble stone. The mortar mixed in with the rubble fill contained hydraulic cement, probably from the Shepherdstown Potomac Cement Mill at Shepherdstown, West Virginia (originally part of Virginia).[13] Since hydraulic cement caused the mortar to set underwater, it was critical to the watertightness of the locks and canals (Fig. 3).

The spandrel stones were 12 to 18 inches in depth with a regular pattern of header stones roughly 4 feet deep tying the spandrel stones to the rubble-stone fill. The exposed stone was a good quality granite brought by the B&O Railroad from the Ellicott Mills quarry (originally called Patapsco) near Baltimore.[14] A beautiful wrought-iron railing, ornamented with scrolls and finials, was installed on the towpath parapet along the river side, and a wooden mule guiderail was installed on the canal side. Timber rub rails were installed on the inside face of the towpath parapet walls to protect the boats.

Maintenance History

A serious leak occurred at one of the abutments of the aqueduct in the spring of 1834, after water was introduced in 1833. The chief engineer, Charles B. Fisk, installed a temporary wooden trunk to allow continued operation of the canal. In 1835 a wing wall collapsed, necessitating another temporary wooden trunk.[15] According to Superintendent W. S. Elgin, the collapse was caused by "heavy laden boats from time to time run[n]ing against the sides."[16] The alignment of the aqueduct may have made it difficult for boats to enter the aqueduct without hitting the parapets.

The persistent leaking prompted Fisk to use a new product called "American Cement," patented by Thomas C. Coyle, to "rebuild" the trunk of the aqueduct.[17] The term rebuild probably meant to coat the inside of the trunk. Nine hundred and twenty-four barrels of this cement were used in the project. This product contained resin and tar and must have been applied hot, as there were costs for using kettles. Legal records from a Baltimore County court in 1838 mention a dissolution of a partnership involving Coyle and a patent for resin cement.[18] Test pits excavated in the trunk for the reconstruction project in 1998 revealed a partial layer of this resin cement at the floor level.

An 1870 Board report to the canal company stated that water was being kept in the canal over the winter, causing ice to form in cracks in the stonework and expand, breaking the bond of the cement and resulting in loose stones.[19] In addition, the ice forming on the surface of the water was most likely forcing out the thinner and lighter berm parapet. The berm parapet was 5 feet wide, as compared to the towpath parapet, which was from 7 to 8 feet wide.

Since the water in the canal was not always emptied for the winter due to a lack of proper maintenance, forces generated by pockets of water freezing inside the rubble fill or by the water in the aqueduct would have been very large.[20] Over the course of several years, these expansion forces would lead to the significant movement of the parapet stones and cracking of the arch barrel. Between 1852 and 1905, Maryland suffered six severe winters, with low temperatures ranging from -5°F in 1852 to -40°F in 1902. In 1857 all rivers in Maryland and Virginia froze over, and in 1905 there were 22 continuous days when the temperature never rose above 0°F.[21]

In 1873 there were further reports of deteriorating conditions at the aqueduct. In 1877, 1886, and 1889 devastating floods caused further damage. The flood damage was so severe in 1889 that the canal company was forced into receivership and was taken over by the B&O Railroad.[22]

Assessment of Contemporary Aqueducts

To fully understand nineteenth-century construction methods and the challenges and problems specific to masonry-arch aqueducts, particularly those that employed elliptical arches, it was important to study other aqueducts of the same period, both on the C&O Canal and in other countries.

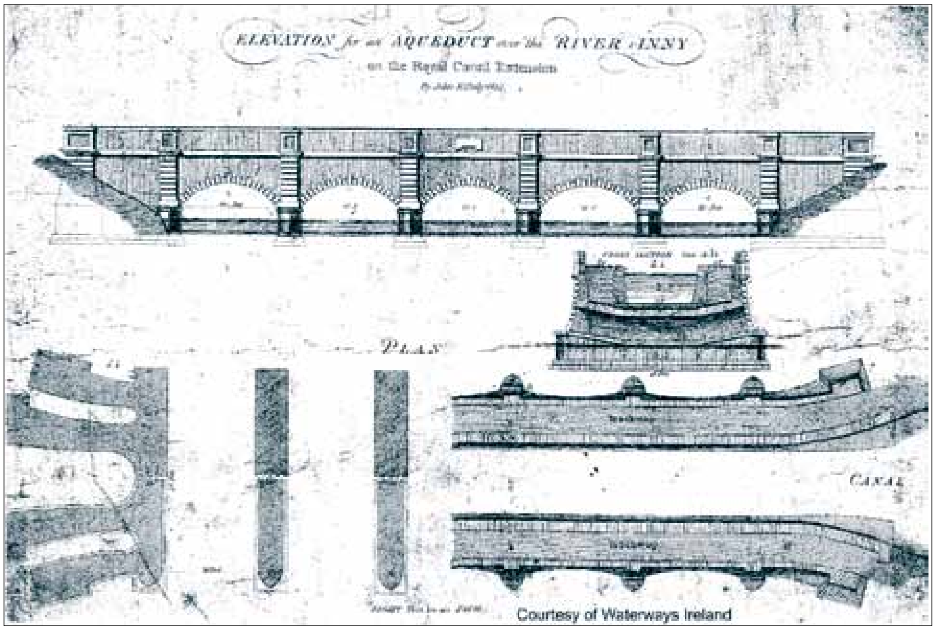


Fig. 4. Elevation, plans, and section of Whitworth aqueduct over the River Inny, County Longford, Ireland, 1814. Courtesy of Waterways Ireland.

Fig. 5. Monocacy aqueduct, Montgomery County, Maryland, 1998. Arch barrel showing longitudinal cracks under the berm parapet prior to stabilization and restoration in 2010. Red arrows indicate two of the temporary tie rods, which were installed under the arches to arrest the transverse movement of the spandrel walls and barrel arches; note also that the cracks are wider at the apex. Photograph by Denis McMullan.

Traditionally, English and Irish canal aqueducts were waterproofed using a thick layer of clay, but supporting the weight of this construction made these structures deep and heavy. An 1814 engineering drawing of a nineteenth-century aqueduct obtained from the archives of Waterways Ireland shows the elevation and cross section of the Whitworth aqueduct, which spans the River Inny in County Longford, Ireland. The drawing illustrates the depth of clay fill and the use of battered spandrel walls to resist the internal lateral earth and hydraulic pressures. The parapets are equal in width on each side and, at 8 feet, significantly wider than the berm parapets on the C&O Canal. The Whitworth aqueduct, like many Irish and English aqueducts, is still intact and carrying water and canal boats (Fig. 4).[23]

The designers of the C&O aqueducts elected not to use the traditional layer of thick clay for waterproofing, choosing instead to depend on the waterproofing properties of the natural hydraulic cement, which is referred to in some historical records as "water cement." They also lined the bottom of the trunk with wood planking, probably as an additional waterproofing measure.[24]

The Antietam aqueduct on the C&O Canal is comparable to the Catoctin aqueduct in that it has a center elliptical arch span that is larger than the two equal elliptical side spans. They are the only aqueducts on the C&O Canal that have elliptical arches and a combination of different arch spans. A slight flattening of the center arch and one of the side arches is noticeable on the Antietam aqueduct, but the arches appear to be stable.

Normally an engineering assessment of an aqueduct or any structure would have the benefit of evaluating most or all of the structure. However, in the case of the Catoctin aqueduct, only a portion of the east arch remained. This was examined but could provide only limited information. Consequently, historic photographs and reports by the original canal engineers and of structural defects common on other C&O Canal aqueducts surveyed by the author formed the basis for the assessment. The most prevalent indications of structural distress on the C&O aqueducts are large longitudinal cracks under berm parapets and smaller longitudinal cracks under towpath parapets (Fig. 5). Cracks as wide as 4 inches have been recorded by the author; they usually run the full length of the arches and decrease in width as they move towards the spring line. Large icicles have been observed hanging from the numerous cracks in the soffit of the arch barrels.

Other common problems on the C&O aqueducts are bulges in spandrel walls measuring up to 10 inches, lateral sliding of spandrel walls of up to 2 inches over the ring stones, settlement along the middle of the coping stones of up to 3 inches, and outward deflection or tilting of the parapets by as much as 4 inches. Individual arch barrel stones protrude six inches or more from many arches, and there is often a significant loss of mortar in the longitudinal joints of the arches but not in the transverse joints, where the mortar is held in position by the compression forces of the arch. Many arches have multiple cracks that have been filled with mortar and concrete in the past. Historic photographs of the Catoctin aqueduct also show significant stone damage at the spring line of the elliptical arch and the

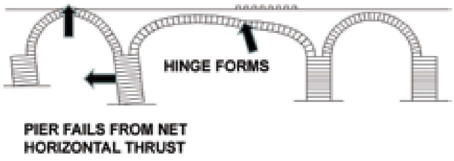


Fig. 6. Catoctin aqueduct, showing sagging central arch, n.d. Courtesy of the C&O Canal National Historical Park Archives.

Fig. 7. Analytical collapse model. Drawing by Denis McMullan.

west pier, possibly indicating crushing failure of the arch stones. Test pits excavated by the author in the trunk of the Monocacy aqueduct and coring in the Conococheague aqueduct revealed a loss of the original cement matrix in the rubble fill, with only tightly packed gravel and sand remaining. There were also numerous voids, especially over cracks in the arch barrel. Testing indicated that the sand contained elements of deteriorated hydraulic lime mortar. Test openings in the parapets of the Monocacy aqueduct revealed that the walls are constructed as two separate wythes with rubble fill between each face. There were also voids and pockets of silt. Voids indicated loss of material, probably through the large cracks in the arch barrel. The silt most likely accumulated from many years of being overtopped by river flooding.

Collapse of the Catoctin Aqueduct

The center elliptical arch of the Catoctin aqueduct had had a pronounced sag at least as early as the 1940s. The berm parapet had collapsed by 1954. The elliptical arch continued to sag until October 30, 1973, when it fell during a local flood and also caused the collapse of the west arch.[25] It is the only C&O aqueduct arch to have exhibited such large deformations and collapse of the arches (Fig. 6).

After the Catoctin collapsed, the C&O Canal National Historical Park retrieved as many stones as possible from the creek and buried them nearby for safekeeping and for future use. They also retrieved bent and broken railings and stored them on-site, partially hidden in the undergrowth.[26]

Structural Assessment

The structural assessment of the Catoctin aqueduct began with an investigation of the bearing strata and the foundations of the piers and abutments. A geotechnical investigation indicated that the abutment and east pier were founded on solid rock with a rock mass quality (RMQ) of good to excellent with unconfined compressive strength values of 7,317 to 15,502 pounds per square inch.[27] Divers in scuba gear conducted an underwater investigation, which revealed erosion of the rock at the interface with the west pier foundation stones.[28] The potential for scouring of the rock under the piers and abutments was investigated by a geologist from the Maryland State Highway Authority, who identified the rock as alternating layers of metadiabase (greenstone-metamorphosed basaltica lava) and mylonite.[29] The greenstone is hard and resistant to weathering in contrast to the softer adjacent mylonitic rock, which is more susceptible to weathering and scour forces. All of the foundations of the aqueduct are bearing on the hard greenstone except the east side of the west pier. The voids under this pier are consistent with its bearing on the softer mylonite rock.

Historic photographs of the Catoctin aqueduct indicate that initially the berm parapet and upstream spandrel wall failed, followed by the center and west arch.[30] The berm parapet failure is common on many of the C&O aqueducts. Of the 11 stone aqueducts, 7 have lost their berm parapets and upstream spandrel walls.

A major problem at the Catoctin aqueduct was the arrangement of the arches: the smaller semi-circular arches on either side of the longer elliptical arch introduced unbalanced, horizontal forces in the structure, resulting in an overturning moment on the piers. Analysis by the author shows that the unbalanced horizontal thrust from the difference in the two span lengths produces a horizontal resultant force of 41 kips per foot acting at the top of the piers. This results in an overturning moment on the piers that causes tension on the one side of the pier. Masonry cannot resist significant tensile stresses, and, as a result, the compressive forces redistribute and cause increased bearing pressure on the opposite side. The maximum bearing stress along one edge of the pier foundation was 45 kips per square foot, a relatively high value, especially considering that the west pier was partially founded on a softer vein of rock.

A computer analysis indicated that as more load was transferred to the arches from the deteriorating stone fill, hinges would form in the arch and at the spring point.[31] Hinge formation would cause deflection of the arch and a redistribution of the compression forces. The arch would probably stabilize in this condition due to the ability of the granite to withstand very high compressive forces. Granite compressive strengths can range from 15,000 to 36,000 pounds per square inch; however, in this case one pier would most likely rotate and the adjacent semi-circular arch would push upwards. Eventually the granite stones at the spring line would fail in compression, or one pier foundation would move to the point that a mechanism would form, causing the collapse of the arch. The deflected shape determined from the computer analysis was similar to the profile of the aqueduct prior to collapse. The analysis indicated the lifting up of the west arch and the tilting of the west pier. The location of the hinges is not the same, but this is probably because of the unknown influence of the mortar fill on the arch behavior (Figs. 6 and 7).

Initially, compressive forces in the elliptical arch were shared by the arch stones and the mortared fill in combination with the stiffening effect of the parapets. The compression in the arch barrel in the direction of the span creates considerable friction forces between the stones that resist transverse lateral forces. This system is effective provided that the fill maintains its integrity. However, in this case, persistent leaking, freeze-thaw cycles, and the loss of cement matrix weakened the fill. The internal hydraulic pressure increased with the growing number and size of the voids, and this pressure, in combination with impacts from boats, eventually overcame the transverse frictional resisting force between the stones, causing the longitudinal cracks in the arch barrels.

As additional stone fill was lost, expansive pressures increased, leading to a reduction in the integrity of the fill. As more of the structure was lost, forces in the arch stones increased; hinges formed in the elliptical arch; and the first signs of sagging would have been noticeable. Eventually the longitudinal cracks were large enough to cause the loss of the weaker and thinner upstream berm parapet. Impact from floating debris no doubt accelerated the process. Once the berm parapet and upstream parapet wall were gone, the interior of the structure was exposed to further deterioration and loss of material. The inherent unbalanced forces most likely caused the west pier to move, resulting in a collapse of the arch.

Rehabilitation Design and Construction

The rehabilitation process followed National Park Service policies including the Secretary of the Interior's Standards and Guidelines for Archeology and Historic Preservation. In particular, the choice of objectives and options for the rehabilitation of the Catoctin aqueduct was subjected to a formal NPS Value Analysis for the purpose of achieving essential functions at the lowest life-cycle cost consistent with required performance, reliability, quality, safety, resource protection, sustainability, and quality visitor experience.[32]

From this process, the C&O Canal National Historical Park determined that the following items were required:

- Restore the missing center arch, west arch, and the berm side of the east arch, including the berm and towpath parapets and railings.
- Restore the west pier and the missing upstream section of the east pier while ensuring that the west pier was on a solid foundation. Both piers needed to be capable of resisting the unbalanced horizontal loading from the center arch.
- Stabilize and repair the remaining east arch, including the stone fill.
- Repair all voids in the bedrock under abutments and piers. Anchor piers to rock.
- Reuse salvaged original stones to the maximum extent possible.
- Replace ring stones in their original locations on the arches.
- Replace spandrel stones in their original pattern and coursing but not location. Use historic photographs to identify coursing sequence.
- Replace coping stones in their original position.
- Ensure the long-term stability and durability of the center elliptical arch.

In order to achieve long-term stability, durability and reliability, the restored structure needed to be capable of resisting water intrusion, freeze-thaw effects, internal hydraulic pressure from future re-watering of the canal, and impacts from boats.

The options of rebuilding the elliptical arch in stone or reinforced concrete were considered carefully. Using stone would have been the more historically accurate solution, but there was a concern about the stability of the elliptical geometry and the practical ability to ensure long-term compression in this arch.

Using concrete in an historic structure can result in compatibility problems, primarily because each material will behave differently during changes in temperature and when subjected to loading. Temperature-change movements are proportional to the material's coefficient of thermal expansion. In this case, the coefficients of thermal expansion of the granite is 4.4 x 10^{-6} per °F, while the concrete has values ranging from 4.32 to 5.02 x10^{-6} per °F. These values are so close that little thermal differential movement will occur. Differential movement can also occur due to different responses to stress. The stress deformation will be proportional to the modulus of elasticity of the material. The modulus of elasticity of the granite is in the range of 2,900 to 8,700 kips per square inch; for the concrete the range is 2,800 to 3,600 kips per square inch. Due to low stress values in the structure and to similar elasticity properties, little internal differential movements were expected from stress. With

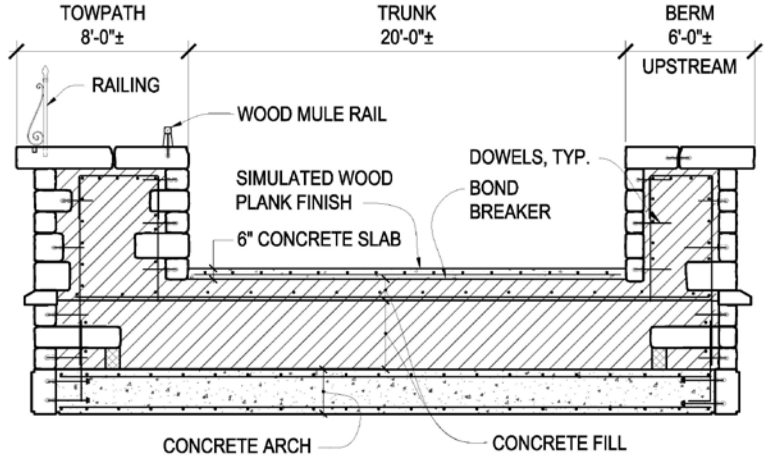


Fig. 8. Cross section of the rehabilitated Catoctin aqueduct. Note that mostly existing stones were used on downstream side, and mostly new stones used on upstream side. Also note stainless-steel dowels connecting stones to concrete fill. Drawing by Denis McMullan.

negligible thermal differential movement and minor stress deformations, there will be very minor internal separation forces. These forces can be easily resisted by the stainless-steel dowel bars connecting the granite to the concrete. In a similar analysis, the concrete fill used to extend the east arch was shown to have very similar properties to the original mortared rubble stone fill in this arch.

The concrete arch, in addition to being 20 percent less expensive, offered a predictable structural behavior, strength, ductility and durability that would assure the longevity of the structure.

The soffit of the concrete arch could have been faced with stone to maintain the original appearance under the arches, but there were concerns about the long-term ability of the connection between the stone and the concrete to withstand impact from large tree trunks swept downstream during flooding. Imprinting the soffit of the concrete arch or coloring the concrete to look like stone were also considered, but, eventually, the honest expression of concrete was preferred. The NPS decided that concrete arches provided the best value consistent with the objectives and policies.

The guidelines of the NPS and of the American Concrete Institute for durability of concrete were followed; the guidelines called for a water-cement ratio less than 0.45, compressive strength of 4,500 pounds per square inch at 28 days, 6 percent air content, and 70 percent cementitious content using Type 2 cement (moderate sulphate resistance).[33] All reinforcing bars were epoxy coated; they were designed and detailed for a minimum of two inches of cover, low stress levels for small crack widths, and adequate space around the bars for ease of installation and good concrete compaction. Coating reinforcing bars with epoxy for additional protection from harmful road salts has been a very common practice in bridge construction for many years, but in retrospect epoxy coating the bars for the arch was probably of little value. Recent testing has shown that there is little to be gained by the use of epoxy coatings.[34] Low-carbon, galvanized, or stainless-steel bars should be used if necessary. The corrosion potential at the aqueduct will not be high, since only occasional maintenance or emergency vehicles will use the aqueduct. Salt will not be applied to the trunk bed, and the structure is not in a marine environment.

A mortared stone fill to replicate the original was not considered sufficiently durable. Gravel was also considered as a fill material; however, it would allow saturation of the fill and the potential for freeze-thaw damage. In addition, gravel, due to its lower density, would have increased the buoyancy of the aqueduct when flooded and reduced the safety factor against uplift and lateral movement.[35] Instead, a low-strength concrete with a 28-day strength of 2,500 pounds per square inch was used. The transverse tensile capacity was enhanced by connecting the stone ties with the continuous cage of epoxy-coated reinforcing, in effect tying the two faces together (Fig. 8).

The first step in the construction project was to install coffer dams around the east and west piers and the west abutment. The remains of the west pier were removed, and the bedrock was examined for soundness. Weak rock was removed. Debris was removed under the edges of the east and west abutments. The east pier and the rock were examined for soundness and voids. Several voids that required repair were discovered; in one case under the west abutment, concrete underpinning was needed. A new reinforced-concrete west pier and an extended east pier were installed with anchor rods inserted into the rock sufficient to resist the eccentric forces. Stone facing was constructed as a permanent form and attached to the poured concrete fill with stainless-steel anchors. The existing remains of the east pier were grouted and pinned to the rock.

> One of the keys to successful reconstruction of the historic arches was the ability to make small adjustments to the formwork in the field to match the irregular profile of the original arches.

The salvaged aqueduct stones were sorted into piles on wood blocking based on their types; however, many original stones were not found. Each salvaged stone was identified by type:

voussoirs (ring stones), keystones, spring stones, arch barrel, parapets, coping stones, spandrel stones, and water table. In order to further identify the ring stones as to arch and placement within the arch, accurate measurements of each stone were necessary. Obtaining consistent measurements proved difficult because each stone had been hand cut and had weathered over the last 170 years, causing rounded edges and uneven surfaces. A device was developed by C&O Canal NHP personnel that significantly improved the consistency of the measurements regardless of who was taking the dimensions (Fig. 9).

Once the stones were measured, they were assembled graphically in a digital model by the author to determine their probable original position within the arch. This modeling required extensive trial and error until a reasonable model could be generated. Then a full-size, rigid-foam version of each stone was fabricated by the C&O Canal NHP and fitted together using the computer-generated arches and historic photographs to help identify the stones. Missing stones were identified and recorded, and their dimensions determined. This process enabled detailed construction drawings to be produced for every missing stone showing its dimensions, finish, and location.

One of the keys to successful reconstruction of the historic arches was the ability to make small adjustments to the formwork in the field to match the irregular profile of the original arches. This capability allowed the formwork for the east arch upstream addition and for the west arch to match the curvature of the existing portions of the arches. The contractor utilized a custom-designed, steel formwork system with hydraulic jacks at 3 feet on center that could be individually adjusted. The new and original stones fit together well and required only minor adjustments. The hydraulic jacks also permitted the controlled release of the formwork to allow the compression forces to transfer gradually to the arch.

The ring stones were held in place with stainless-steel anchors attached to the rear of the stones and cast into the concrete arch. The spandrel stones were laid on top of the ring stones in their historically correct pattern and in the same coursing but not necessarily in the same location. The concrete arch was placed using small lifts to avoid displacing the ring and spandrel stones. The stones from the inside faces of the parapets were differentiated from those on the outside spandrel walls by rub marks from canal boats or bolt holes. Once a level surface had been achieved at the top of the arch, the parapet stones were installed, and concrete fill placed inside the finished cut stones. It was possible to replace towpath coping stones in the original position due to the presence of iron clamps and other markings on the stones. Over 450 original stones were used in the rehabilitation. Stones that could not be used were buried on site to preserve them for future generations. Granite from the Mason Quarry in Mason, New Hampshire, was used for the new stone. Although the new stone looks quite different beside the original stone, it will blend in over time (Fig. 10).

The top of the concrete fill was sloped from the center of the aqueduct to each end, where site drains carry water outside the canal prism. The historic floor construction of the aqueduct would have been timber planking, but maintenance considerations led to the use of a concrete slab scored to represent the planking.

Historic Railing

The original wrought-iron railing pickets were set in holes drilled into the coping stones approximately 6 inches from the edge of the stone and set at 8 inches on center. They were set in lead. Due to a combination of rust and freezing water expanding in the hole, the original coping stones had cracked along the line of the posts, and the edges of the coping stones had fallen off. The canal company had made repairs by setting the railings farther back from the edge of the parapet stones and supported them with metal straps wrapped over the parapets. Furthermore, during floods, the railings caught debris, causing the coping stones to be pulled off the parapet and into the river.

Fig. 9. Measuring device for arch stones, 2011. Photograph by Dan Copenhaver, C&O Canal National Historical Park.

Fig. 10. New ring stone in place, 2011. Photograph by Denis McMullan.

Fig. 11. Catoctin aqueduct after rehabilitation was completed, 2011. Photograph by George E. Lewis, Jr.

Some changes to the design of the original railing were thus necessary. The new railing needed to be removed quickly in the event of a flood warning, and the pickets spaced closer together to comply with the International Building Code safety requirements. In order to be rapidly demountable, the railing was designed in sections, with each section being 5 feet 4 inches long and having 14 pickets at 4½ inches on center; each section was lapped over the end of the adjacent section. None of the sections could be removed without removing the first section, then the second section, and so on. The first section was locked in position. Staff at the C&O Canal NHP demonstrated that they could remove the entire railing in less than one hour.

The posts and sleeves set into the stones were stainless steel; the finials were cast iron, and the remaining scrolls and plates were carbon steel. The scrolls, finials, and pickets matched the size and shape of the original railing. All elements were cleaned to commercial blast clean standards of the Society for Protective Coatings-Sophisticated Paint Endorsement (SSPC-SPE) with a minimum blast profile of 1½ mils. The railings received one primer coat of high-solids epoxy and a finish coat of black aliphatic polyurethane paint, all applied in the shop under controlled conditions.

Conclusion

Work on the Catoctin aqueduct was completed in 2011 and appears to have weathered several floods and freezing temperatures well.

The C&O NHP assigned an experienced stonemason and construction engineer to oversee all quality control at the site. Their involvement and the selection of a highly qualified contractor, Corman Construction, Inc., and their masonry subcontractor, Lorton Stone, LLC, were critical to ensuring satisfactory completion of the structure (Fig. 11).

The Catoctin aqueduct had failed as a result of a combination of factors: an unbalanced arrangement of arches, unreliable waterproofing techniques, weak arch geometry, and a soft layer in the bedrock under the west pier. The failure to use a layer of clay as waterproofing appears to have been a serious misjudgment in the original design and is a common problem in all of the C&O Canal aqueducts. The method developed for this project to measure and locate recovered stones in ring arches will be useful in future arch restoration projects.

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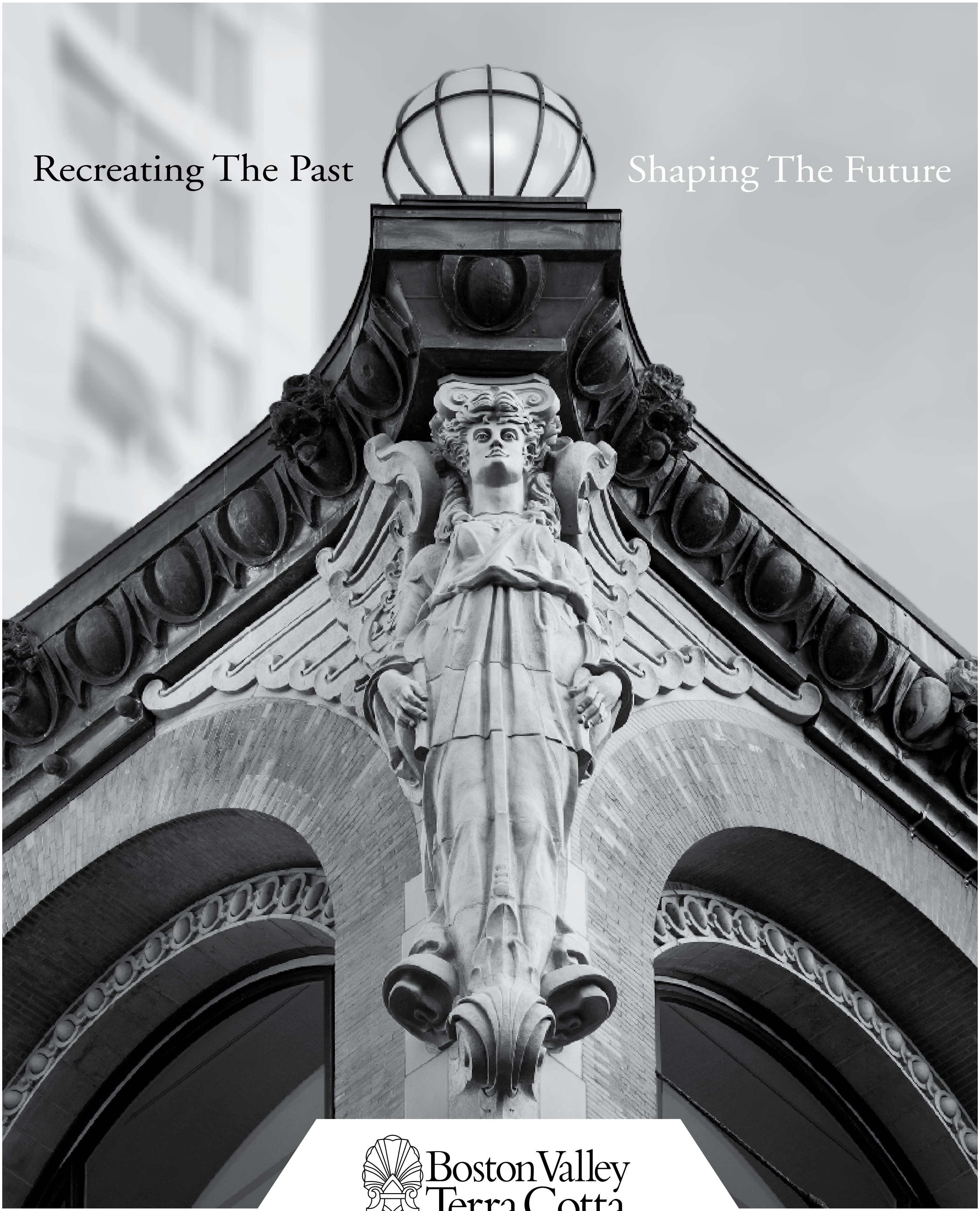

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