Evaluation of Structural Damage

Reinforced Concrete Arch Culvert

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The Duck Creek Phase III flood protection project presented the Corps of Engineers' Louisville District with numerous difficult challenges in design, contracting and construction. In addition to these conventional challenges, sections of the culvert, the centerpiece of the effort, were accidentally overloaded and damaged during construction. This article overviews the structural evaluation of the damaged culvert. A subsequent article, in a future issue of STRUCTURE® magazine, will present the repair methods used to restore the structural capacity and serviceability of the culvert.

The purpose of the flood protection project was to lower flood elevations by eliminating an oxbow bend in Duck Creek, an urban stream located on the east side of Cincinnati, Ohio. The proposed long-span culvert, designed to carry flood flows around the existing creek channel bottleneck, was oriented parallel to, and in several locations was nearly underneath, the centerline of an adjacent, relocated roadway (*Figure 1*). The culvert had to be constructed with 1) very little cover, which presented a challenge to the precast culvert designer and manufacturer, and with 2) restricted space within the contractor's work limits for the storage of overburden material from the culvert excavation.

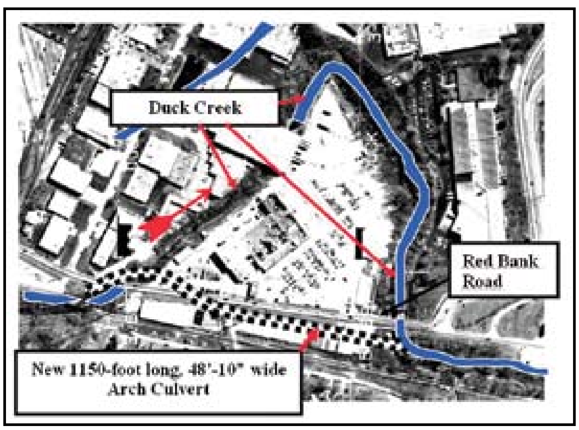

Figure 1: The Duck Creek Culvert eliminates an oxbow in an urban stream, and is constructed in a congested site bounded by a railroad track and an existing highway.

The construction contract was awarded to Ahern & Associates of Springfield, Ohio on May 30, 2002. Once detailed shop drawing development started after contract award, the prime contractor found that overhead clearance issues with the new Red Bank Road subgrade were going to create conflicts with the standard 48-foot CON/SPAN® section that was specified by the Corps of Engineers. The extensive length of the culvert allowed a custom, lower profile cross-section to be designed that optimized the balance between the required hydraulic performance, the overhead clearance and its structural efficiency. Thus, Ahern selected a prototype long span culvert design developed by CON/SPAN® Bridge Systems.

The Corps of Engineers designed the cast-in-place base slab and knee walls upon which the precast culvert elements were to be placed, using design loads from CON/SPAN® Bridge Systems. BridgeTek fabricated the 161 arch segments, each 49.75-feet wide, 11-inches thick and approximately seven feet long, at their Wilder, Kentucky outdoor precasting facility. A typical cross-section of the culvert is shown in *Figure 2*.

Figure 3: One of several distinct overburden stockpiles placed over the Duck Creek Culvert.

The construction of the culvert proceeded with Ahern performing a sequential operation. The base slab was constructed in segments generally between 100 and 140 feet long, with the majority being 126 feet. For each base slab segment, Ahern performed an excavation of the overburden, prepared the subgrade, cast the base slab, placed 14 to 18 precast arch elements (*Figure 3*) and backfilled the arch with imported select granular fill. Installation of as many 18 arch segments was routinely performed in a single long day. Each base slab and arch placement cycle took approximately one to 1½-months.

In late July of 2004, Ahern's quality control manager noted some spall damage on the inside of the culvert. A preliminary check showed that a large overburden stockpile had inadvertently been placed over the top of the culvert in an area that had been completed and backfilled several months prior (*Figure 3*). The Corps and Ahern reviewed their archives for site photographs from the previous year, to see if any other stockpiles had been placed over the culvert. The photos showed several distinct stockpiles that covered about 400 linear feet of the 1150 foot long culvert. It was inferred by the Corps that the stockpile had simply been moved as required so the contractor could continue to proceed with other work on site. Aerial photos of the stockpile were taken and a field survey was completed. The maximum stockpile height was approximately 15 feet, with the maximum height over the culvert of about 12 feet. The culvert had been designed for a maximum dead load of four feet of earth.

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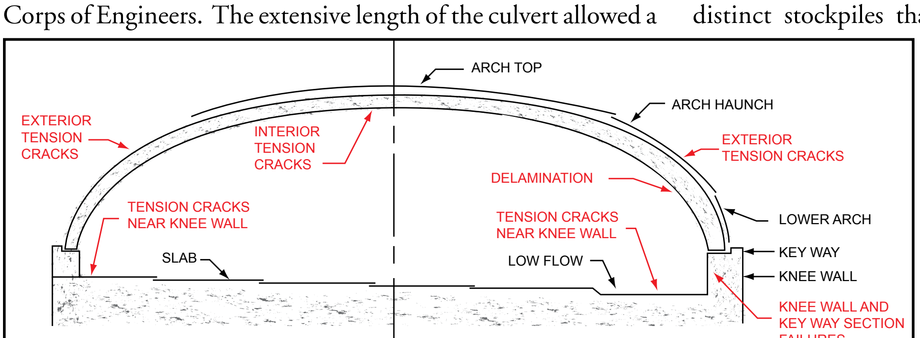

Figure 2: Key plan and damage map. The Duck Creek Culvert typical section. The precast concrete arch elements are placed on top of the knee walls, which were cast monolithically as part of the cast-in-place base slab.

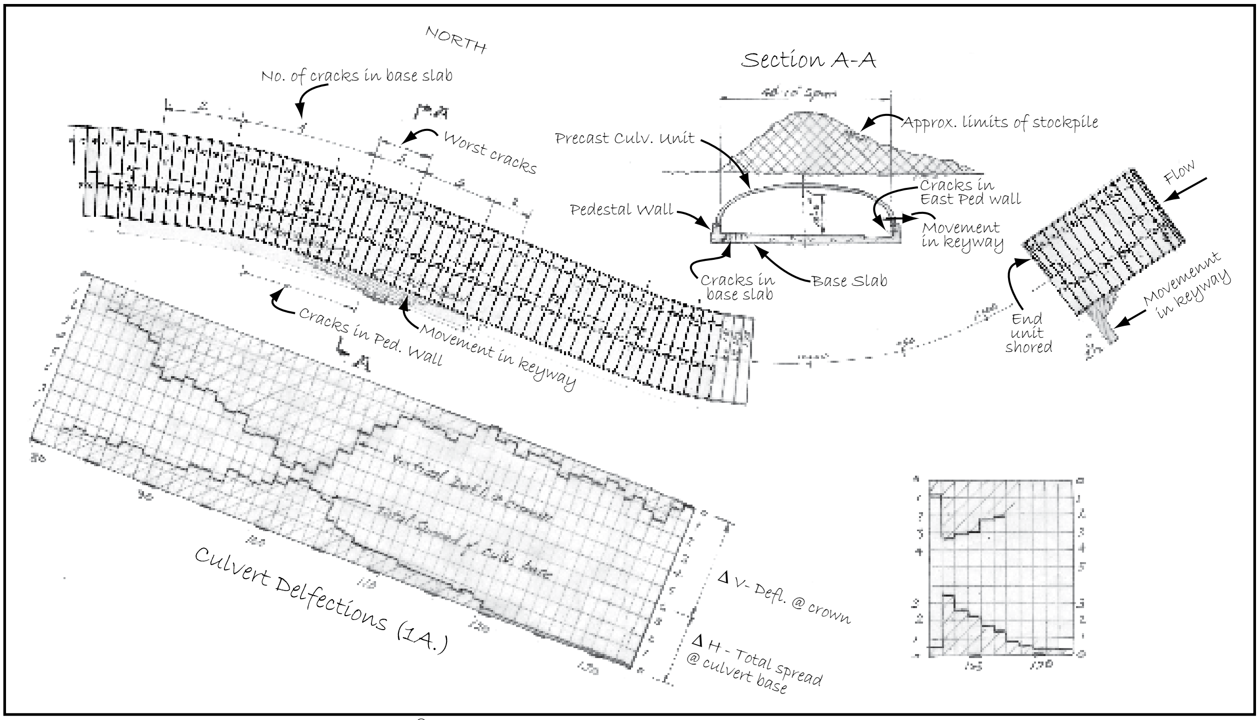

Figure 4: Field notes prepared by CON/SPAN® summarizing visually observable and measurable damage to culvert precast elements, base slab and knee walls.

Ahern procured the failure investigation services of CTLGroup and coordinated a thorough and detailed inspection of the entire culvert. Findings from this investigation were used by the parties to design and construct repairs, restoring the structural performance of the arch.

Structural Investigation Overview

A preliminary damage survey provided a summary of the type and extent of visible damage (*Figure 4*). A detailed site investigation followed and considered five potential types of structural distress, as listed in the Condition Assessment that follows.

The investigation used nondestructive testing (NDT) in addition to conventional visual investigation techniques and coring. The NDT methods are detailed in the American Concrete Institute Report, ACI 228.2R-98 *Nondestructive Test Methods for Evaluation of Concrete in Structures*.

Inspection

Conventional

A visual inspection was conducted on the interior and exterior of precast arch units, as well as the knee wall and slab. This inspection included general observations of cracks in the slab, knee wall and arch, measurement of movement of the arch units relative to the knee wall and uninstrumented hammer sounding of the arch. Detailed crack maps were developed for areas of apparent and potential distress.

Ultrasonic Pulse Velocity (UPV)

The UPV method was used to evaluate the depth of cracks in the base slab. The tests focused on two cracks that ran parallel and in proximity to the west knee wall. These two cracks were deemed to be among the most significant from the visual inspection, with widths up to 0.015 inches.

The UPV method uses two transducers, one placed on each side of a crack. The transmission of an ultrasonic pulse from one transducer to the other can be correlated to the depth of the crack. The reference pulse velocity for undamaged concrete was estimated at a region of sound concrete prior to testing at crack locations.

Based on the results of UPV tests of these cracks, the maximum depth was estimated to be 13 inches, while the majority of the crack depths were within approximately 5 to 10 inches. Two core samples, taken at the points of maximum UPV readings, showed the crack depths of 8 and 9 inches. This indicated that the UPV readings provided a conservative measure of the crack depth.

Impact Echo (IE)

The IE method was used to evaluate the presence of delamination in the knee wall and near the base of arch segments. The method uses a small impactor to generate a stress wave in the tested element. A reflection of this stress wave is generated from the back face of the element, as well as from any significant internal discontinuity.

The test was performed at the intersections of a 2-foot grid on the arch units. The density of reinforcing steel in the arch units added a degree of complexity to the interpretation of the signals. Selective coring was used to confirm the data interpretation.

Analysis of the IE test results on the arch elements showed significant internal delamination only at those units with visible damage on the interior surface. Surprisingly, even with the severe overload of approximately 50 precast arch units, only four were significantly damaged.

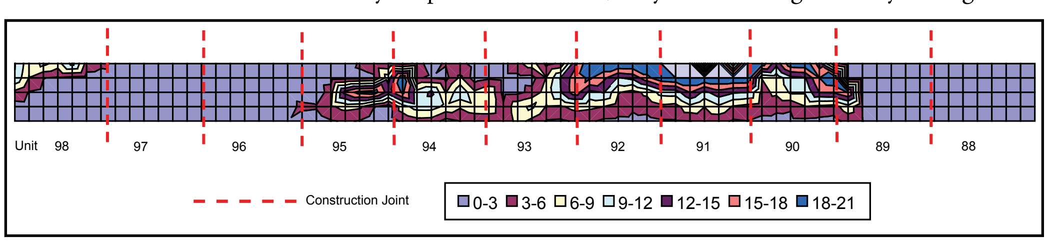

Figure 5: Graphical representation of typical Impulse Response (IR) data, showing region of elevated mobility (and associated potential damage) in the knee wall.

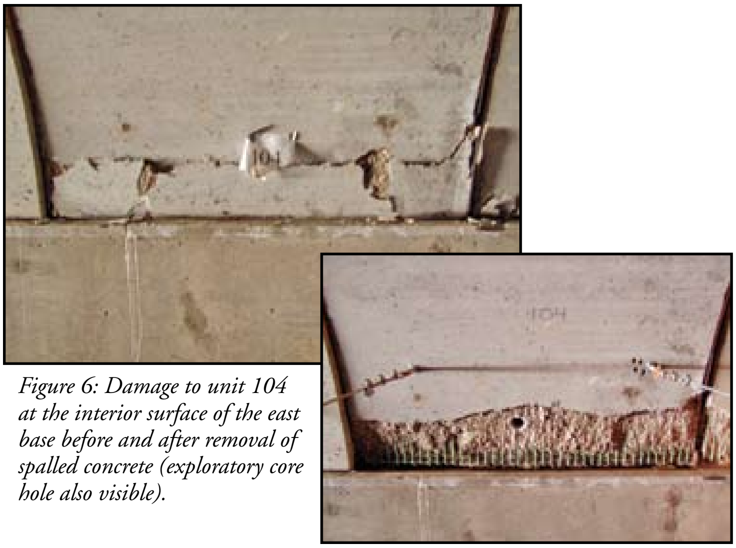

Figure 6: Damage to unit 104 at the interior surface of the east base before and after removal of spalled concrete (exploratory core hole also visible).

The IE test was found to be ineffective when testing the knee wall, due to its relatively large thickness and the associated large attenuation of the transmitted stress wave.

Impulse Response (IR)

The IR method was primarily used to evaluate structural uniformity and the presence of internal damage or defects in the knee wall. The IR method is similar to the IE method, but uses a higher energy impact from an instrumented hammer and measures the structural response of the tested element, rather than the transmission of the stress wave. The equipment for this investigation measured mobility as the IR parameter. Mobility is an indicator of stiffness based on the velocity response to the impact excitation. Higher mobility values indicate decreasing stiffness. On the knee walls, the IR tests were conducted from the interior face on a 1-foot horizontal by 0.5-foot vertical grid.

For a continuous section of knee wall with sound concrete, average mobility values were less than 2. Values greater than 4 indicated concrete anomalies within the knee wall. The IR testing was not capable of detecting the relatively superficial effect of failure of the knee wall key way, and was also sensitive to variability in the stiffness provided by the backfill material. The IR testing proved effective at identifying significant cracking in the knee wall. Results corresponded well with visual observations and coring. The test results were ultimately confirmed after the knee wall was exposed during the demolition operations (which were guided by the IR results). *Figure 5* shows sample IR data.

Ground Penetrating Radar (GPR)

The GPR survey was used to evaluate the locations of reinforcing bars, to facilitate the coring operation and avoid damaging the reinforcement.

Coring

Cores were extracted from multiple locations in the slab, knee wall and arch with nominal diameters including 2, 3 and 4 inches. The purpose of the cores was to verify limits of damage indicated by the other inspection methods.

When cores contained unexpected cracks, the core holes were examined to determine whether the cracking was due to distress during the coring process. Cores taken in the east knee wall identified limits of shear failure and those from the base of the arch identified limits of delamination. Cores from the top region of the arch and from the slab indicated that the tensile cracks in these regions did not compromise the structural integrity of the section. The majority of the cracks in the slab propagate around the aggregate. This implies that they occurred soon after the concrete was cast, while the concrete was still relative-

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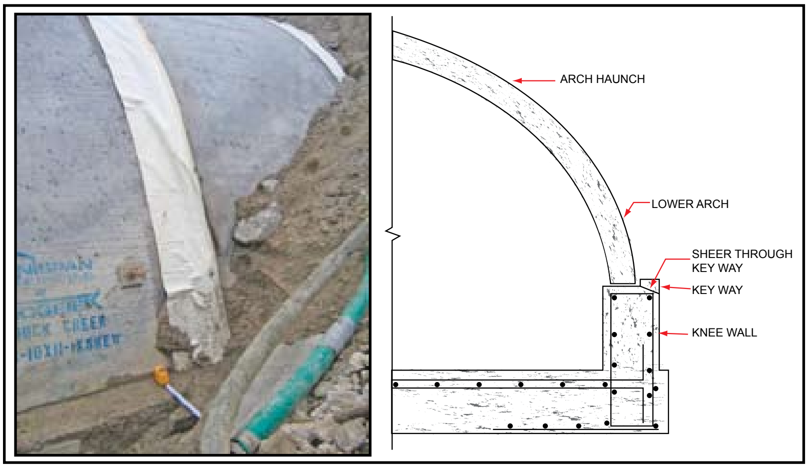

Figure 7: Key way failure

ly weak compared to the aggregate, and are likely due to thermal differences and drying shrinkage associated with placing large quantities of concrete.

Condition Assessment

1. <u>Tension cracking at the interior surface of the top of the arch</u>: The interior of the arch exhibited minor hairline cracking based on crack mapping of selected interior and exterior units and cores. The cracks were completely closed, implying that the arch geometry was elastically restored from the overloading and that the reinforcing steel likely did not yield
2. <u>Tension cracking at the exterior surface of the haunch of the arch</u>: Cracking in this region appeared minor and consistent with a cracked-section design.
3. <u>Shear failure at the base of the arch in the form of delamination of the precast concrete from the steel reinforcement</u>: Damage of this type was limited to units that were subjected to the highest loading. *Figure 6* shows a damaged unit before and after the spalled concrete had been removed, revealing the damage to be limited to the outer layer of concrete. The interior layer of rebar on one unit had been plastically deformed along the failure plane in the concrete.
4. <u>Knee Wall</u>: Separation between the arch units and the interior grout pack of the knee wall was documented at a majority of the overloaded units. This implied a failure of the key way (*Figure 7*). Complete failure of the knee wall was identified in regions that were highly loaded (*Figure 8*). The balance of the knee wall in the affected area had damage that transitioned from the relatively minor key way failure to the full section failure.
5. <u>Tension cracking at the top surface of the slab in the vicinity of the knee wall</u>: Coring observations, combined with the UPV data, indicated that the cracking in the slab was primarily of the sort that would be expected from casting mass quantities of concrete (temperature and shrinkage cracks). The cracks developed into a flexural pattern in proximity of the knee walls in the highest loaded region. Cracks in these regions may have developed under the action of gravity loads transferred from the knee wall during the overload. However, cores taken through cracks in these regions also had indications of being generated by thermal effects (the cracks were very tight and propagated through the aggregate). The cracks were generally less than 0.015 inches and most were hairline with no offset, implying no yielding of the reinforcing steel from tensile or shear strains.

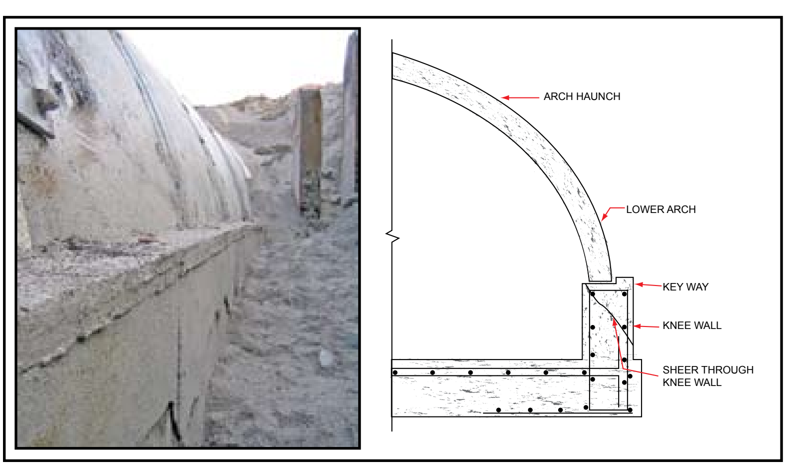

Figure 8: Knee wall shear failure.

Conclusion

A combination of conventional and nondestructive test methods allowed for a timely and economical evaluation of damage to the precast and cast-in-place elements of the arch culvert. The degree of damage and logistical constraints required targeted repairs to be conducted in a two-phase program. The types, location and sequencing of repairs were dictated by the results of this assessment and will be presented in a future issue of STRUCTURE®.▪

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