INNOVATIVE DESIGN FOR AN ARCH BRIDGE WIDENING

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ABSTRACT

This paper describes the innovative design of an arch bridge widening project which applied state-of-the-art technology by combining the proper analysis of the existing skewed arch structure behavior with the use of advanced light-weight concrete and a well-planned construction sequence. After conducting an in-depth review of the existing structure and the load condition, the design engineers made an innovative proposal to the client that would save significant costs and shorten the construction schedule. The engineers proposed keeping the existing arches and replacing and widening only the upper portions of the bridge. In order to minimize the load to the existing substructure, the engineers selected lightweight cellular concrete to replace the existing heavier soil fill in the arches. According to the client[1], this design eliminated the need for a complete bridge replacement, therefore shortening the project duration by approximately 4.5 years, and saving the taxpayers almost $5 million dollars[2].

KEYWORDS:

Arch Bridge, Widening, Light Weight, Low Density Cellular Concrete, Quartic Function, Fill, Innovative, Load Distribution, Construction Sequence

INTRODUCTION

Snohomish County’s South Slough Bridge #91 is a skewed two-span concrete arch structure located 40 miles north of Seattle in rural Snohomish County, Washington. The existing arch bridge is 22’-4’’ wide with two 80’ spans and a total length of 222’ at the centerline. The reinforced concrete deck is 19’-4’’ wide between curbs with two lanes of traffic, each 9’-8’’ with no shoulders. Each arch has a rise of 14’ and the total height of the bridge from the foundation to the top of roadway is 23’-6’’. See Figure 1.

The bridge was built in two sections. The first arch was completed in 1918. In 1920, the bridge was lengthened with the addition of the second arch on its south side. The original north arch was likely modified in 1920 during construction of the south arch; however, there are no plans available for the 1918 construction of the north arch to verify this.

The south span roadway slab sat on soil fill atop a reinforced concrete arch, with reinforced spandrel walls on either side. It appears that this was also the original construction of the north arch. However, the 1920 construction plans for the north arch seem to indicate that when the south span was added the soil fill was removed and replaced with concrete support ribs. It was unclear why this was done or how these supports were anchored to the arch.

Both arches rest on concrete abutments which are founded on piles. At the center abutment the south arch was designed to rest partially on “shoulders” cut into the original abutment as well as a new 8’ long portion of the abutment sitting on 24 new piles. The south abutment is 22’ long and is supported by 83 piles but the number of piles at the north abutment and north half of the center abutment is unknown. See Figure 2.

It was an elegant and sturdy bridge when built in 1918, but an inspection in 2005 by the Snohomish County Public Works Department deemed the bridge functionally obsolete and identified it for replacement with a wider structure to meet current safety and design standards. See Figure 3 for the existing bridge picture. The Public Works Department of Snohomish County has selected Parsons Brinckerhoff, Inc. as their consultant for design and construction support of this project.

MAJOR CHALLENGES AND ENGINEER’S SOLUTION

The design team and the client faced two major challenges: insufficient funding and tight schedule. A rough estimate indicated that the bridge replacement could cost near 6 million dollars. Since the bridge is located in an environmentally sensitive area, the required environmental study and permitting process associated with the replacement could potentially stretch the project duration to 4.5 years. Since this bridge is a major link for the local community, the client wanted this project to be completed during the summer when the schools are not in session.

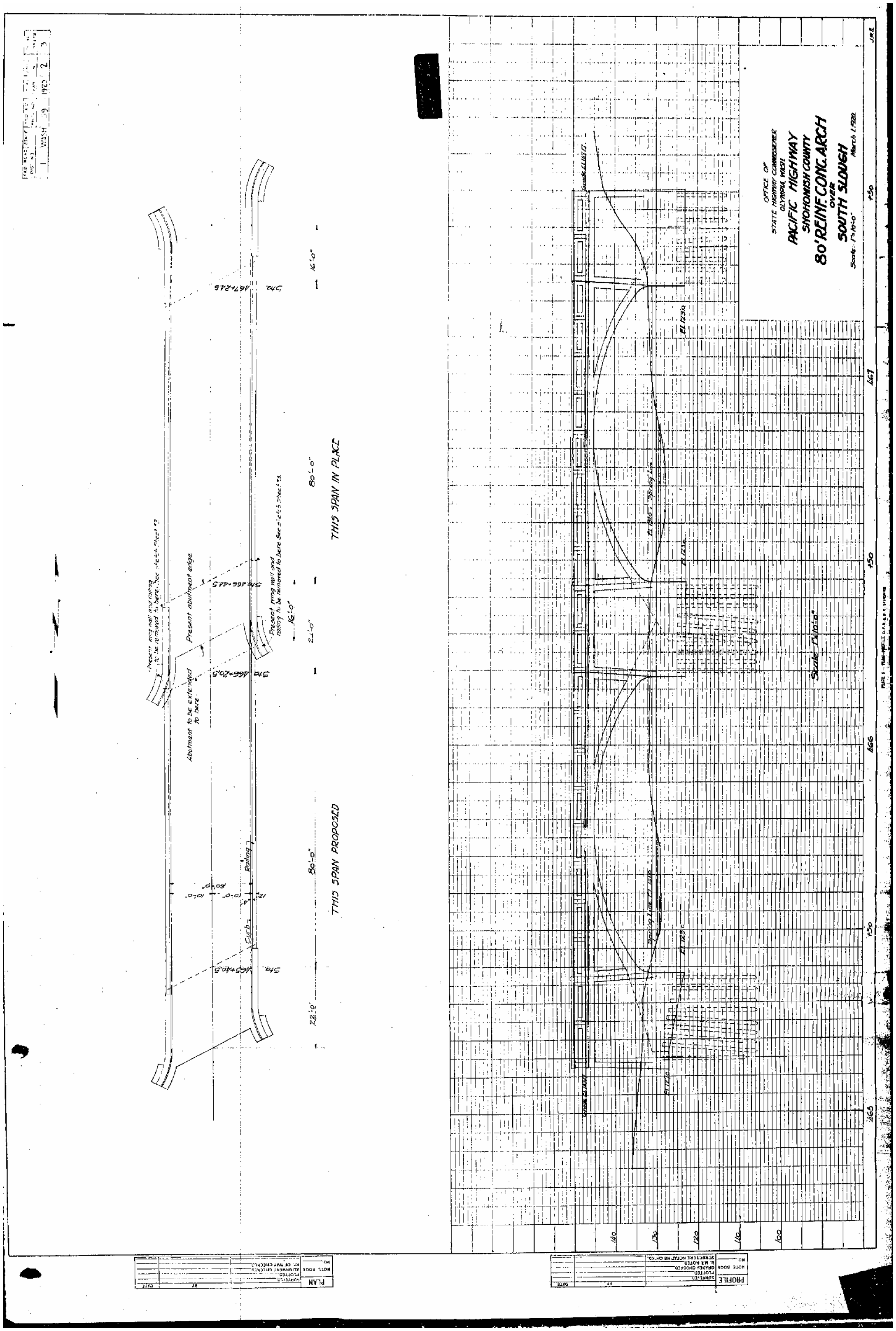


Figure 1. Existing Bridge Plan and Elevation

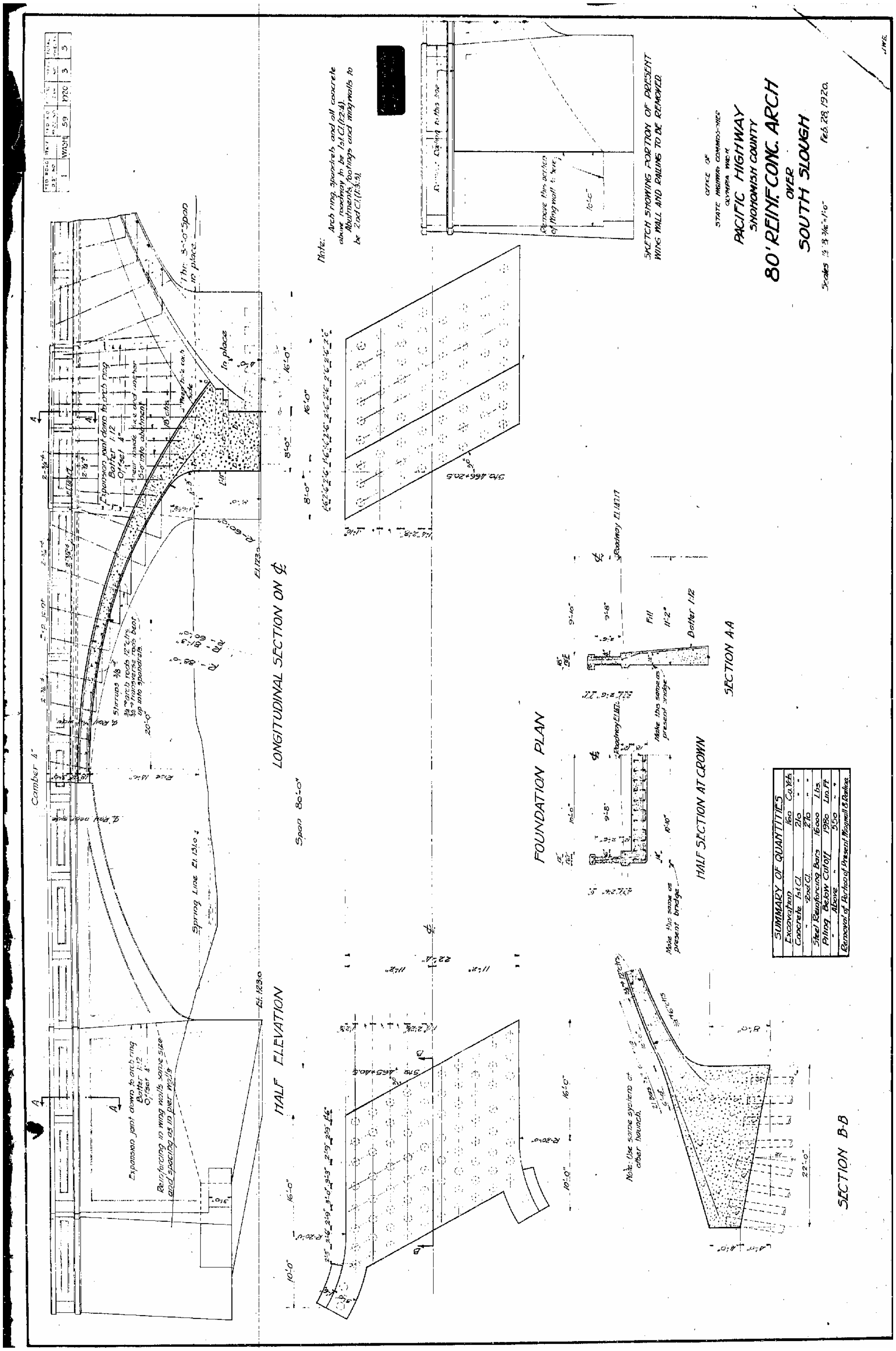


Figure 2. South Arch Elevation and Foundations

Figure 3. Existing Bridge (Looking South)

After conducting an in-depth review of the existing structure and the load condition, the design engineers made an innovative proposal to the client that would significantly reduce cost and shorten the construction schedule. Although the inspection had revealed several major deficiencies of the bridge, the Luten arches and their foundations appear structurally sound. The possibility of keeping the existing arches and replacing only the upper portions of the bridge interested the design engineers. The engineers proposed keeping the existing arches and replacing only the upper portions of the bridge. Two essential requirements had to be met in order for this proposed option to be successful. First, the new design had to maintain approximately the same dead load distribution on the original arches to keep them in compression. Second, the load increase on the substructure and foundations had to be minimized to reduce the risk of excessive settlement. Although arch bridges are expected to tolerate increased dead and live loads, there was concern among the engineers since the original design and construction records were not available to verify the capacity of the bridge.

Pre-cast concrete slabs that would form the wider deck would also add a substantial amount of weight to the bridge. To counterbalance the additional dead load, engineers needed to find a way to reduce weight somewhere else. They studied several light weight materials, including engineered styrofoam and several types of light weight concrete, to replace the existing heavier soil fill in the arches.

Engineered Styrofoam was considered as it has a very low density of approximately two pounds per cubic foot (pcf) in contrast to 120 pcf for soil. The extremely low weight of this material would minimize the load increase on the existing structure. However, it was not known in what condition the top surface of the arches would be once the soil was removed. This, and the fact that the ribs were curved and skewed, would make the on-site installation and quality control of the pre-formed Styrofoam blocks a challenge. Because of this concern and the need for a weight that would keep the arch in compression, the Styrofoam option was eliminated.

Lightweight cellular concrete has significantly less density than soil fill, approximately 30 pcf for lightweight concrete versus soil's 120 pcf. An additional advantage included that the concrete could be formed in place to create an even contact on top of the existing structure. A cellular concrete produced by mixing an expansion material to a cement mixture was chosen for the project. The result is a low-density (load-reducing) material used as fill for applications such as behind retaining walls, at bridge approaches, over culverts, under roadways and over poor soils. The density ranges from 30 to 110 pcf; Normal compression strength can range from 140 to 2400 psi, depending on what is required for the application.

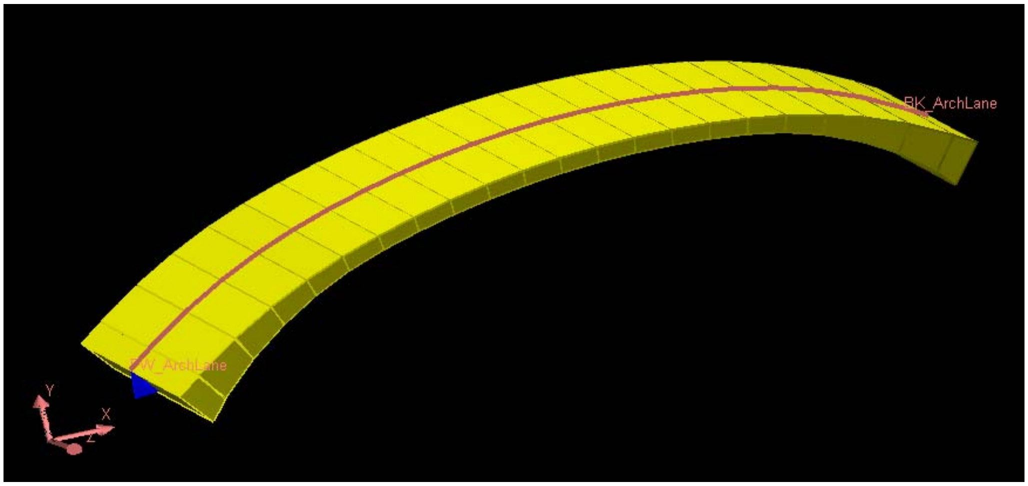
ANALYSIS METHODS

The bridge widening design was performed in accordance with the AASHTO LRFD Bridge Design Specifications, 3rd edition. The new widened precast deck planks are designed for HL93 live loading and the following dead loads:

- Self weight of the deck plank (39.7 kips).
- Asphalt overlay superimposed dead load of 50 lbs/ft^2 over the central 28 feet of the slab.
- Railing superimposed dead line load of 320 lbs/ft acting at both outer edges of the slab.
- Superimposed dead line load of 120 lbs/ft acting at both outer edges of the slab representing possible future utilities.

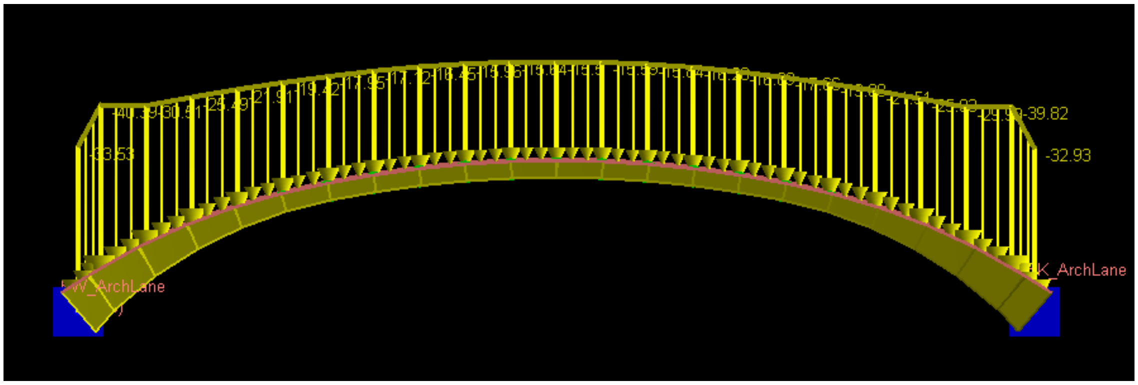
In order to make the innovative design work, the capacity of the existing arch structure has to be verified with the existing loads and the new dead loads and other design loads. A load comparison between existing bridge and the proposed widened bridge has to be studied as well. The analysis of the main arch span was conducted by two methods. One was an analytical method, the other was a finite element analysis.

Per geometrical analysis of the existing arch, the function that describes the centerline of the existing arch is a quartic function, not a parabolic function. And the dead loads the arch is subject to can also be represented by a quartic function. The analytical solution was produced by establishing equations of equilibrium and then integrating the strain energy function. Within the program used for the finite element analysis the arch was represented as a single "Spine" of wide beam elements. Plate elements were not used because neither the program used, nor any other FE program accessible to the designers was capable of analyzing tapered plate elements. Additionally, it was felt that it was more important to capture the effect of the variable stiffness along the length of the arch due to changes in the arch depth rather than considering transverse effects that would be captured by plate elements. In essence, this is a plane strain problem. Arch geometry and member thicknesses were determined from the as-built drawings supplied by the client.



Load is applied to the structure in three ways:

1) The distributed load due to arch self weight, fill weight, and superstructure weight is applied as trapezoidal loads on the beam elements which approximate the quartic load function outlined in the analytical solution.



2) On the north arch, a uniformly distributed load is applied over the center section of the arch to represent the effect of the existing slab that was to remain in place at the request of the client.

3) The HS-20 truck loading is applied using influence line analysis. Two influence lines are defined, one in the north-south direction, and one in the south-north direction. The finite element program scales the result from the unit influence load by the effect of the HS-20 truck axles with variable spacing, and envelopes the results on the maximum and minimum load effects. For this analysis, we are concerned with the

bending moment in the arch. All pure axial forces in the arch are compressive and relatively small, hence it is only the effect of bending moments, that give rise to tensile stresses within the section, that must be carried by the reinforcement.

The arches are built into the abutments and the top rebar is doubled within 10’ of the abutments. The bending stiffness of the arch has a profound effect on the moment distribution, and for this reason, cracked section properties are used. It was found during the course of the analysis that the best course of action was to use cracked section properties based on service loading. If cracked section properties based on ultimate loading are used then the moments on the arch redistribute in such a way that the bending stiffness used are overly conservative. This is a non-linear problem and difficult to solve by trial and error, but using bending stiffness based on service load is a good intermediate approach and is realistic with respect to the actual loading that the bridge will be subject to.

After the finite element analysis is complete, the results (enveloped to determine the maximum and minimum moment effects) are copied into an Excel spreadsheet. The spreadsheet sums the axial force effects for each load case described above and divides by the arch width. Section analysis is performed on a 1’ wide strip of arch.

INNOVATIVE CONSTRUCTION TECHNIQUES

A correct load distribution and a well-planned construction sequence were essential for the success of this proposed construction method. To maintain the integrity of the arches and ensure safety during construction, the process of removing existing soil fill from the arches and replacing it with the lighter cellular concrete had to be conducted incrementally in 2 to 4-feet lifts, alternating between the arches. The following is an overview of the construction sequence:

1. Removed existing pavement and concrete bridge slab.
2. Partially removed the existing parapet; used the remaining portion as a form for the new light-weight concrete fill.
3. Removed the existing soil fill in uniform lifts, alternating from one arch to the other to maintain a balanced distribution of weight. See Figure 4 for demolition.
4. Filled arches with lightweight concrete in uniform lifts, again alternating from one arch to the other.
5. Laid a layer of 6’’ compacted crushed rock surface top course to serve as the leveling base for the new pre-cast concrete slabs. See Figure 5 for the backfill.
6. Placed the thirty-two 8’ wide pre-cast concrete planks and asphalt joint filler on top of the crushed rock, installed tie rods between planks as plank placement progressed, working from the center outward. Placement of the precast deck planks is shown in Figure 6.
7. Placed asphalt pavement and the new galvanized steel guardrail system.

Figure 4. Demolition

Figure 5. Backfill with Low Density Cellular Concrete

Figure 6. Lay the Precast Concrete Deck Planks

ENVIRONMENTAL CONSIDERATIONS

The modernization, not replacement, of the bridge was a great practice in sustainability. Keeping the bridge's footprint intact reduced the ecological impact a full replacement would have had. Widening the existing bridge kept construction out of the wetlands and out of the floodplain. Banks were re-vegetated with native shrubs.

The two photos below, Figures 7 & 8, show how keeping the construction out of the floodplain greatly reduced any environmental impact.

Figure 7. Before (Looking North)

Figure 8. After (Looking North)

CONCLUSIONS

The innovative design of the Snohomish South Slough Arch Bridge widening project applied state-of-the-art technology by combining the proper analysis of the existing skewed arch structural behavior with the use of advanced light-weight concrete and a well-planned construction sequence. According to the client, this design eliminated the need for a complete bridge replacement, therefore shortening the project duration by approximately 4.5 years, and saving the taxpayers almost $5 million dollars.

The most significant accomplishment of this project was delivering a product by innovative design that satisfied both the client and surrounding community by coming in years ahead of schedule and millions of dollars below the cost of total replacement[3]. The finished project increased the square footage of the deck by 62 percent on top of the existing arches and also reduced impact to the surrounding sensitive environment. See Figure 9 for an aerial view of the new bridge.

Figure 9. Aerial View of the New Bridge

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Michelle Main, Design engineer, Parsons Brinckerhoff

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