I-35 Bridges Over the Oklahoma River
Long Span Bridge Type Study

Northbound & Southbound Bridges

Prepared for Poe & Associates

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DRAFT SUBMITTAL

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1 INTRODUCTION

Poe & Associates, Inc. (Poe) is providing preliminary engineering services to the Oklahoma City Department of Transportation (ODOT) in association with the Dallas Junction Project in Oklahoma City, OK. This project includes an assessment of viable long span signature structure types that do not require a pier in the Oklahoma River. Alfred Benesch & Company (Benesch) has been retained by Poe to complete the initial study of long span bridge types suitable for the replacement of the northbound (NB) and southbound (SB) bridges of I-35 over the Oklahoma River. This study includes a comprehensive assessment of the existing project site and geometric constraints that impact development of a viable long span bridge type. The study assesses several long span bridge types and their applicability to this river crossing location. Of the bridge types assessed, the two most suitable are carried forward for a more detailed analysis which shall include initial designs, construction feasibility considerations, and cost comparisons. The study concludes with a recommendation for bridge type to be advanced based on the assessment of site constraints, cost, and constructability for a long span river bridge at this location.

2 PROJECT SITE & GEOMETRIC CONSIDERATIONS

2.1 Project Location

The structures to be studied carry I-35 SB and I-35 NB over the Oklahoma River. The project site is roughly 1.5 miles east and 0.5 miles south of the Downtown Oklahoma City area. Additionally, the project site is just south of the I-35/I-40/I-235 interchange (Dallas Junction Interchange), making the proposed structures important links in the overall transportation network of the Oklahoma City Area. Key stakeholders near the project site include, but are not limited to: The Oklahoma City Boathouse District, The Native American Cultural Center, and The OKC National High Performance Center.

FIGURE 1 - PROJECT LOCATION

2.2 Existing Structures

2.2.1 Existing SB Structure

The existing I-35 SB bridge is comprised of a PPC beam superstructure and multi-column reinforced concrete piers supported on drilled shafts. The structure consists of eight spans and carries four lanes of traffic and two shoulders across the river. Of the eight spans, two are south of the river, five are over the river, and one is north of the river. The structure is 802’-6” long and varies in width from 71’-0” out to out at the south end to approximately 99’-0” out-to-out at the north end. Spans 1 and 8 are 101’-3” long and Spans 2 thru 7 are 100’-0” long. All substructure units are skewed 16° left ahead.

2.2.2 Existing NB Structure

The existing I-35 NB bridge is comprised of a PPC beam superstructure and multi-column reinforced concrete piers supported on drilled shafts. The structure consists of eight spans and carries four lanes of traffic and two shoulders across the river. Of the eight spans, two are south of the river, five are over the river, and one is north of the river. The structure is 802'-6" long and varies in width from 71'-0" out to out at the south end to approximately 114'-6" out-to-out at the north end. Spans 1 and 8 are 101'-3" long and Spans 2 thru 7 are 100'-0" long. The substructure units are not skewed.

2.3 Proposed Geometry

2.3.1 Geometric Constraints

Due to the increased importance of the Oklahoma River to the adjacent state of the art rowing facility, one of the key objectives is to remove any piers/obstacles in the river that could impede rowers. The Oklahoma River at the location of the proposed I-35 bridges is approximately 450' wide from bank-to-bank.

2.3.2 As Given Roadway Geometry

The proposed SB roadway and structure is skewed approximately 106° relative to the river while the proposed NB roadway and structure is skewed approximately 97° relative to the river. Both the SB and NB roadways will carry six 12' traffic lanes and two 12' shoulders with additional ramp tie-ins at the north end of the river crossing. See **Figure 2** below for a plan view of the as-given proposed roadway geometry, including identification of the tie-in ramps.

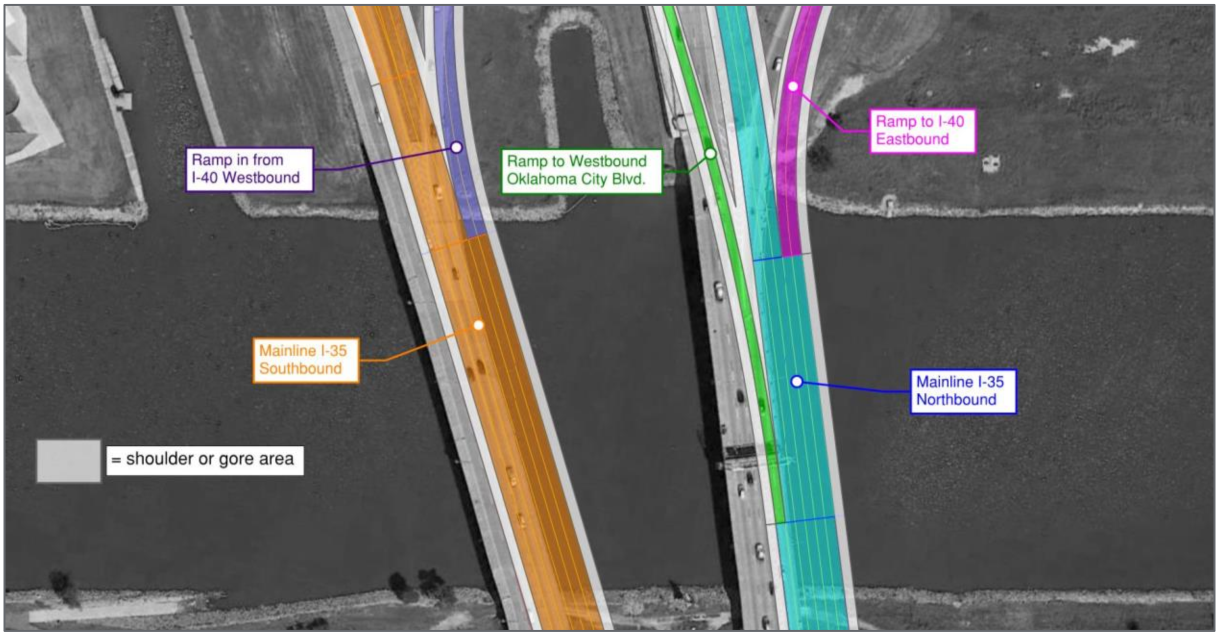


FIGURE 2 – AS-GIVEN PROPOSED ROADWAY GEOMETRY

One ramp that was closely considered within this bridge type study was the ramp from I-35 NB to I-40 EB. Three potential alignments for this ramp were developed by Poe and provided to Benesch for consideration (see **Figure 3**). The alignment shown and considered for this study for the EB I-40 off ramp was decided to be the Option 2 alignment. Option 2 was chosen as the as-given ramp alignment for this bridge type study because of significant drawbacks associated with Options 1 and 3, most notably:

- Option 1: This alignment diverges off I-35 NB near the midpoint of the river crossing, leading to a river span structure width that is not viable for the bridge types being considered.
- Option 3: The divergence point north of the river is most favorable to a long span river bridge; however, the ramp design speed required for this alignment is lower than desired.

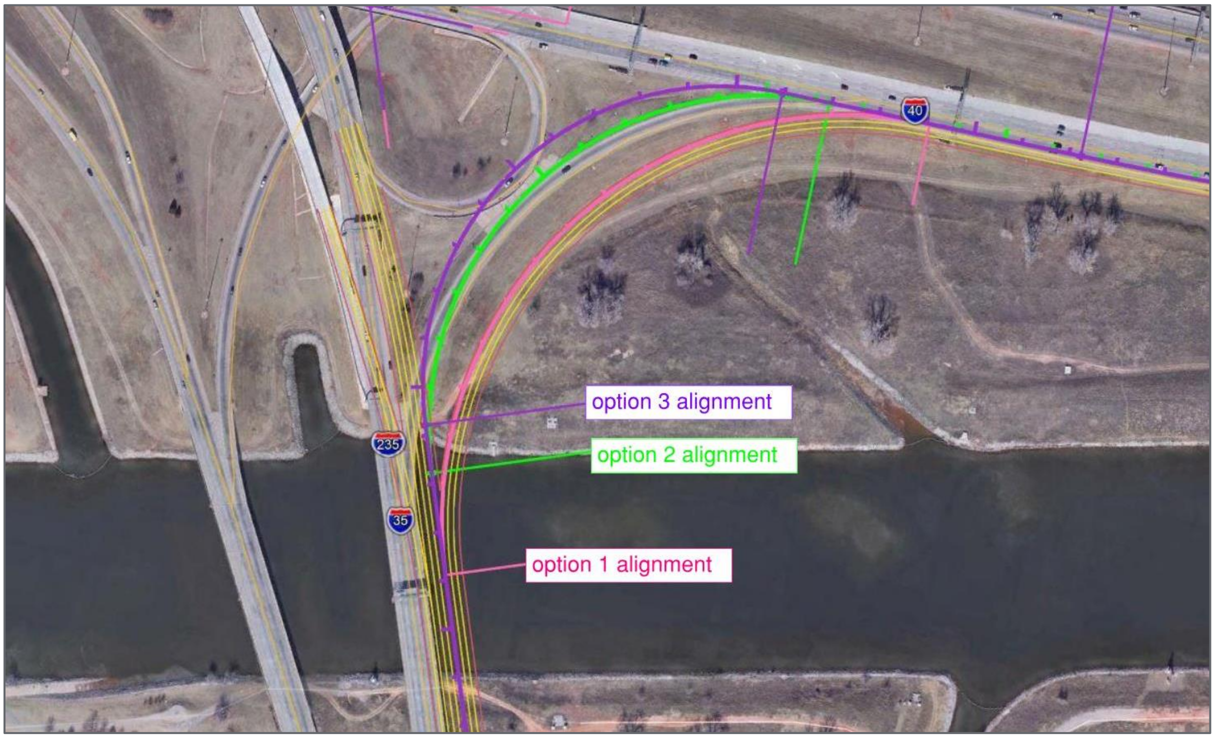


FIGURE 3 - I-40 EB OFFRAMP ALTERNATES

2.3.3 Effect of Proposed Ramp Alignments on Structure Width

Long span bridge types cannot practically accommodate a variable width of structure across their main spans; they must be overbuilt to accommodate the widest point of the roadway that will be in place on the main span. Because of this, the geometry of the ramp tie-ins at the north end of both I-35 SB and NB control the overall structure width for the river span (i.e. any increase in structure width at the north end for ramps will require an increase in width at the south end of span). While it would be desirable to move the north pier of the river span as far south as possible to avoid the ramp tie-ins, the location of this pier is constrained by the desire to keep the pier outside of the river.

At the I-35 SB structure, the required increase in width for the structure to span the entirety of the river is negligible (less than 2’). This is because the divergence of the ramp and mainline happens mostly north of the river bank. However, at the I-35 NB structure, this effect is significant. Maintaining the alignment of the Oklahoma City Blvd. ramp (peeling off the northwest end of NB I-35) while keeping the north pier out of the river will require an overbuild of bridge width that exceeds 25 feet (see **Figure 4**). Accommodating the extra width on the river span would significantly increase cost along with constructability challenges due to both a larger overall bridge area and a less efficient superstructure. For the purposes of this study, it is therefore assumed that the Oklahoma City Blvd. ramp must be re-aligned (and thus reconstructed) to shift the I-35 tie-in further north beyond the limits of the river span (see **Figure 5**).

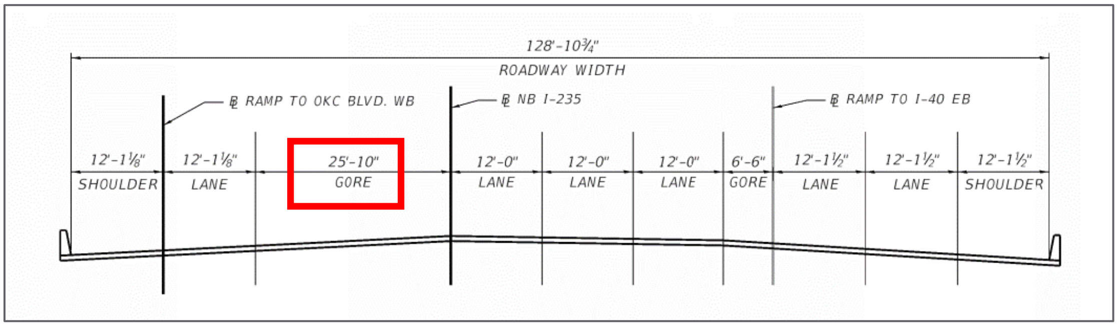


Figure 4 – I-35 NB Roadway Configuration at North Pier (as-given)

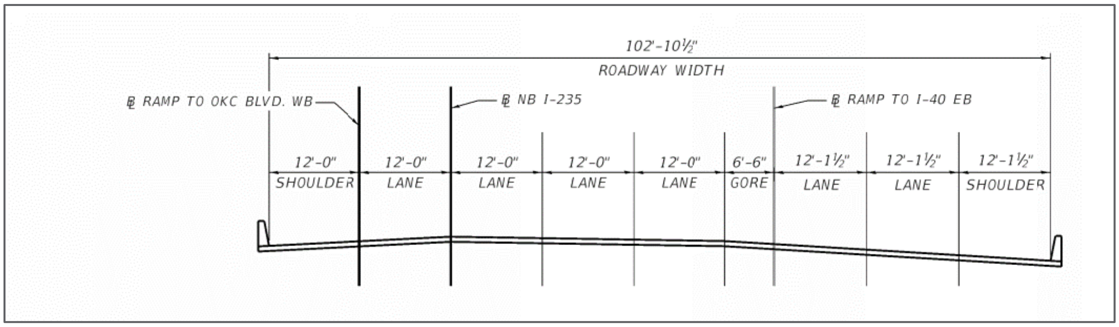


Figure 5 – I-35 NB Roadway Configuration at North Pier (shifted OKC Blvd. ramp alignment)

3 INITIAL BRIDGE TYPE ASSESSMENT

The span lengths for I-35 NB and SB over the Oklahoma River are approximately 520 ft. Several feasible bridge types for these span lengths were considered and the findings are presented in the following sections. Feasible and optimal span length ranges for various bridge types are shown in **Figure 6** – Feasible and Optimal Span Lengths by Bridge Type.

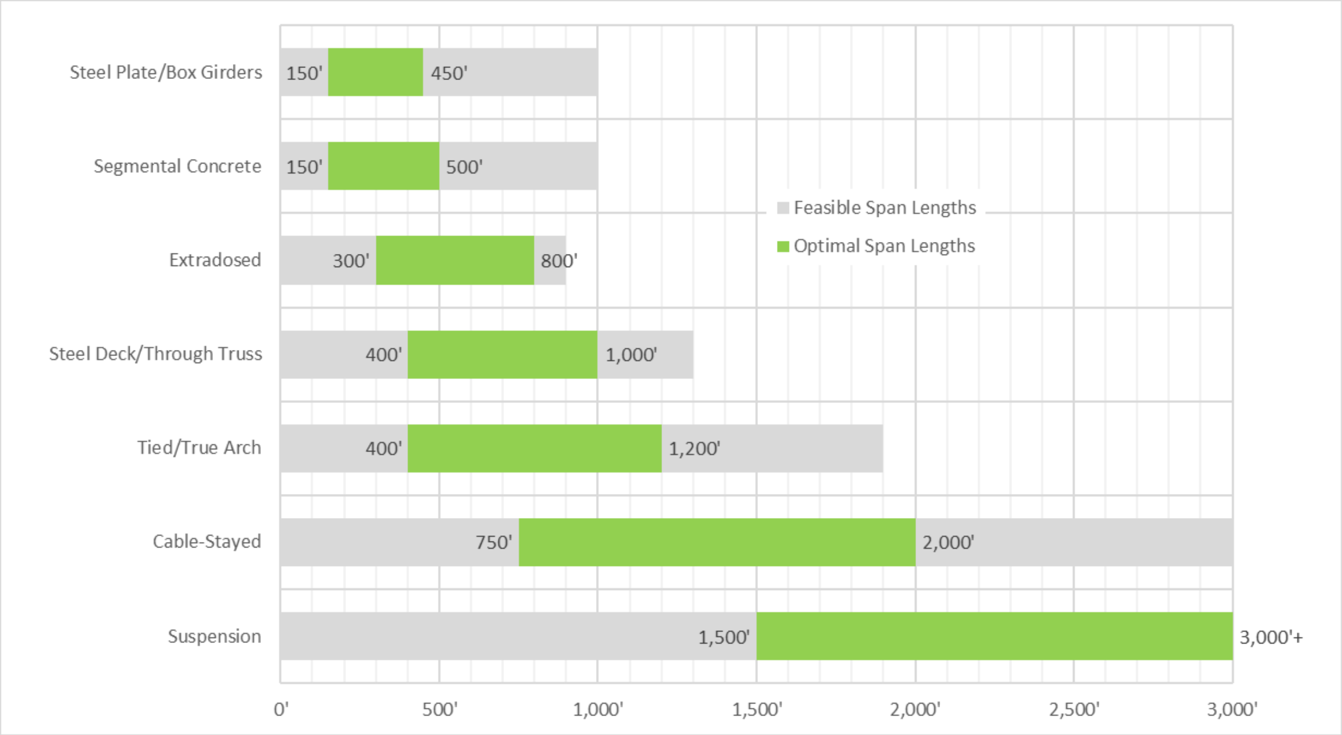


FIGURE 6 – FEASIBLE AND OPTIMAL SPAN LENGTHS BY BRIDGE TYPE

3.1 Steel Plate/Box Girders

Steel girder bridges typically consist of multiple lines of welded plate or box girders beneath a concrete deck. The multi-girder configuration eliminates any fracture-critical considerations and facilitates staging with the existing structure. Contractor bids are generally competitive as most are familiar with this type of construction.

Site constraints for I-35 NB and SB over the Oklahoma River present significant drawbacks for steel girders. The interchange ramps to the north do not allow for additional continuous spans north of the river, resulting in a highly impractical and inefficient span over the river. A vertical profile raise would also be required to accommodate an increased superstructure depth without further reducing the vertical clearance over the waterway. If minimizing temporary obstructions in the river is a priority, it should be noted that temporary shoring in the river would be required to support the various girder segments during erection.

FIGURE 7 – STEEL PLATE GIRDER BRIDGE

3.2 Segmental Concrete

Segmental concrete girders have become more popular in various parts of the country. Short segments of concrete box girders are precast off site and shipped to the project location. These segments are then hoisted by crane or gantry into position and post-tensioning is used to hold them in place. Erection proceeds piece by piece in this manner until the span is complete. Shop fabrication offers improved quality control and many bridges can be constructed using cantilever construction without additional temporary shoring. Concrete bridges also offer improved durability and reduced inspection and maintenance requirements when compared to steel.

FIGURE 8 – SEGMENTAL CONCRETE BRIDGE (GO BETWEEN BRIDGE)

Like steel girders, site constraints for I-35 NB and SB over the Oklahoma River present significant drawbacks for segmental concrete girders. The lack of additional continuous spans north of the river results in an inefficient design and hinders cantilever construction methods. Both a vertical profile raise and temporary shoring in the river would be likely.

3.3 Extradosed

Extradosed bridges are relatively uncommon, combining aspects of both cable-stayed and segmental box girder structures. Cables are attached between the box girders and short pylons extending above the level of the deck. The pylons tend to be significantly shorter than cable-stayed bridges. The hybrid structure is constructed using the methods described for segmental concrete bridges with the added step of attaching pairs of cables to the free end as segments are erected. Due to the added support from the cables, a shallower superstructure can be achieved than with segmental concrete girders alone. Proper tensioning of the cables is critical for this structure type.

As the pylons for extradosed bridges need to be tied to back spans, the inability to provide additional spans to the north hinders the feasibility of this structure type for I-35 NB and SB over the Oklahoma River. Using a single pylon at the south bank is feasible; however, the optimal span lengths presented in **Figure 6** – Feasible and Optimal Span Lengths by Bridge Type are then halved to 150 ft to 400 ft and this extradosed configuration becomes inefficient.

FIGURE 9 – EXTRADOSED BRIDGE (KWIDZYN BRIDGE)

3.4 Steel Deck/Through Truss

Truss bridges consist of a series of straight members connected with gusset plates to create a highly rigid structure. Trusses have been used for many years in highway and rail applications, although their popularity is waning. Through trusses, with the entire truss at or above the roadway, can meet the existing profile without significantly impacting vertical clearance. Conversely, deck trusses are located below the roadway and would require a significant profile raise to avoid reducing the existing vertical clearance over the river. Fabrication and transportation of components is often easier than other signature bridge types and they can be constructed using geometric control methods with no jacking or tensioning required. To facilitate staging and maintenance of traffic, the entire superstructure can be erected off alignment on shoring and moved into position via barge or lateral slide.

Trusses meet the site constraints and optimal span lengths for I-35 NB and SB over the Oklahoma River, but there are several drawbacks to consider. The bridge must be a constant width and the widened deck section for the ramps at the north end will drive up the overall bridge area. Significant inspection effort is required due to the bottom chord and various vertical and diagonal members being designated as fracture-critical.

FIGURE 10 – STEEL THROUGH TRUSS BRIDGE (ALBERT GALLATIN MEMORIAL BRIDGE)

3.5 Tied/True Arch

Tied and true arches use a curved arch rib to suspend the deck with hangers. True arches, relying upon the foundations to resist horizontal thrust at each end, were eliminated from consideration for these I-35 structures due to excessive substructure demands and tighter fabrication and erection tolerances. Tied arches are preferred for this site as the horizontal thrust is resisted by tie girders along each side of the deck. Like trusses, tied arches may be erected off alignment and moved into their final position.

FIGURE 11 – TIED ARCH BRIDGE (BROADWAY BRIDGE)

Tied arches are very appropriate for I-35 NB and SB over the Oklahoma River. Drawbacks for arches include the same constant width limitation as trusses. Arches also carry slightly more fabrication, transportation, and erection requirements. During certain stages of construction, hangers will require jacking or tensioning to establish correct loads. The tie girders are also fracture-critical members and will carry additional inspection requirements.

3.6 Cable-Stayed

Cable-stayed bridges support the roadway using cables connected directly to tall towers. The proposed span lengths are below the optimal range for this type of structure as shown in **Figure 6**; however, the range presented assumes a tower on both sides of the main span. Cable-stayed bridges can be asymmetric with a single tower at one end of the main span. For the I-35 bridges, a single tower at the south bank would be a reasonable alternative that eliminates the need for tiedown back spans on the north side of the river. It also allows a wider deck at the north end beyond the last set of cable stays. Construction can be performed in stepwise manner without shoring, building short lengths of deck and installing pairs of cables, until the main span and back spans are complete.

Achieving the proper balance of cable forces is key for efficiency and a short back span to the south may present challenges. Tilting the tower away from the main span can help in this regard. As these bridges cannot be constructed off alignment and moved into place, careful consideration of staging and maintenance of traffic is paramount before selecting this structure type.

FIGURE 12 – CABLE-STAYED BRIDGE (FLEHE BRIDGE)

3.7 Suspension

Suspension bridges are one of the oldest long-span bridge types and are typically reserved for spans exceeding 1,500 ft. Towers are constructed from which the main catenary cables are strung. Hangers supporting the deck are attached directly to the main cables. In construction, this allows the towers and main cables to be built prior to incrementally installing the hangers and deck.

Aside from the inefficiencies at this span length, the back span required on the north side of the river is not achievable. These bridges must also be constructed in place with corresponding impacts to staging and maintenance of traffic.

FIGURE 13 – SUSPENSION BRIDGE (ROBERTO CLEMENTE BRIDGE)

3.8 Initial Bridge Assessment Conclusions

There are several bridge types that are suitable based on span length for the proposed reconstruction of I-35 over the Oklahoma River, but only a few of these bridge types warrant further consideration based on the project constraints. Steel plate/box girders, segmental concrete, extradosed, and suspension do not fit well with the geometric constraints of the project site and/or would be highly inefficient.

Tied arches and trusses share multiple advantages and disadvantages. Similar advantages include the ability to construct these bridge types off alignment without reliance on back spans. The biggest disadvantages are the increased structure width to accommodate ramp geometry and the inclusion of fracture-critical members. For this study, a tied arch has been selected over a truss based on recent DOT trends and fewer fracture-critical members.

A cable-stayed bridge with a single tower offers a true alternative to a tied arch, with contrasting advantages and disadvantages. The cable-stayed advantages include a lack of fracture-critical members and a reduced deck footprint tied more closely to roadway geometrics. However, cable-stayed bridges must be constructed in-line which impresses the duration of impacts to traffic.

Tied arch and cable-stayed bridge types for the I-35 SB and NB crossings of the Oklahoma River will be explored in more detail in the following sections.

4 TIED ARCHES

4.1 Structure Description

The curved portion of the bridge above the deck is referred to as the arch rib and it transfers the weight of the bridge and its loads primarily though axial thrust along the member. In a tied arch, tie girders running along each side of the deck resist the horizontal component of the thrust at the abutments or piers. Hangers connect the arch rib to the tie girder, which also supports the floor system and deck.

4.2 Proposed Geometry

To span the entirety of the Oklahoma River, the proposed I-35 SB and NB tied arches have been laid out with a span length of approximately 520'. This falls in the range of optimal span lengths for a tied arch bridge (see **Figure 6**). Under a uniformly distributed load, the optimal height of the arch would be 1/3rd of the total span length – approximately 170' tall. In reality, the loads that will be placed on the arch will not be uniformly distributed. For more conventional bridge loadings, the optimal arch height becomes shallower, approximately 1/5th of the span length. Many arch bridges in use today follow this span to height ratio quite closely. Consequently, the optimal arch height for both the proposed I-35 SB and NB tied arch structures is approximately 105'.

The out-to-out deck width for the proposed structure is approximately 103' for the NB structure and approximately 98' for the SB structure. As mentioned in Section 2.3.3, the out-to-out width of the deck is governed by the geometry at the north end of the structure, where ramp alignments diverge from the mainline.

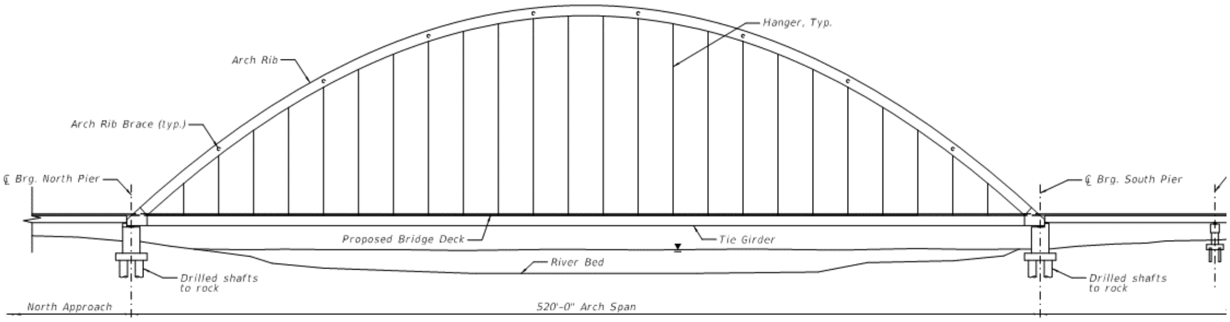


FIGURE 14 – TIED ARCH ELEVATION VIEW

4.3 Superstructure

4.3.1 Arch Ribs

The curved arch ribs span over the bridge deck and support the top end of the hangers. Loads are carried primarily through axial thrust along the ribs, but varying amounts of shear and flexure are also resisted. Flexure can be minimized through careful cambering of the arch and tie such that the final deflected shape of the arch rib closely matches the ideal thrust line.

Arches can be vertical or tilted inwards in a basket-handle configuration. Vertical arches are often simpler to design and detail but have a reduced buckling resistance, as the opposite arch ribs tends to buckle in the same shape. Lateral bracing between the arch ribs is used to improve buckling and wind resistance for both configurations.

Arch ribs are typically constructed of welded steel box sections. The interior is often detailed to allow access for fabrication, inspection, and ventilation. Hanger plates extend into the ribs and require careful detailing for proper force transfer and fatigue resistance. For typical arch bridges of similar span length and magnitude to the proposed I-35 bridges, the arch rib box sections range from 4’ to 6’ deep and 3’ to 6’ wide. Longer spans or a different aesthetic may be achieved by using round or trussed arch ribs.

FIGURE 15 – BRIDGE WITH VERTICAL ARCH RIBS (I-280)

4.3.2 Tie Girders

The tie girders run along each side of the deck and are supported by the arch hangers. One of the primary roles of the tie girders is to resist the horizontal thrust component of the arch ribs. As such, gravity loads will only induce vertical reactions on the substructure. The tie girders also frame into the floor system that supports the deck.

For a time in the 1980s and 1990s, the design community hesitated to use tied arches as total collapse would be expected if the tie girder failed. With better detailing practices and the development of tougher steels, most of these concerns have been alleviated.

The tie girder is typically a box or I-section. The depth of the box or I-girder sections for arches of similar magnitudes to the I-35 bridges are typically between 6’ and 9’. Box girder sections are easier to detail with internal redundancy. This may be achieved by over-designing the tie as a built-up member of individual plates. Unlike a welded girder, fracture in one of the plates would not be expected to propagate throughout the entire tie girder. Box girders can also be detailed with internal post-tensioning strands that will carry the load if the box section fails. Spans greater than those required for this project have also been achieved using post-tensioned concrete tie girders.

4.3.3 Hangers

Hangers are used to suspend the tie girders, floor system, and deck from the arch ribs. Vertical hangers are most common. Networked hanger systems use diagonal hangers with a “trussed” appearance that can increase the efficiency of the structure.

Most modern bridges use structural strand with anchorages at each end. The bottom anchorage typically allows length adjustment during construction. Each hanger can also be detailed with two separate strands per location. This facilitates hanger replacement while the bridge is still supporting traffic and provides redundancy if failure occurs.

Hanger vibrations may be induced by wind loads. Mitigation methods, if required, typically require some type of damper system. Monitoring may be used to determine the need for mitigation and to verify the performance of those measures after installation.

FIGURE 16 – ADJUSTABLE SINGLE STRAND HANGER INSTALLATION

4.3.4 Floor System

The floor system is comprised of transverse floorbeams spanning between tie girders and longitudinal stringers between floorbeams. The transverse floorbeams are often welded plate girders and the web depth can be varied to match the cross section of the roadway. Longitudinal stringer spans are often short enough to make rolled beams viable. The floor system and deck are not part of the primary force resisting system of the arch. Lateral bracing of the floor system is provided to facilitate construction and future deck replacement.

4.4 Substructure

Due to the limited vertical clearance under the existing bridge, a solid wall pier with pilasters beneath the arch bearings is a reasonable assumption for this site. The wall between the pilasters will support a series of girders from the approach spans. Loads on the pier will primarily be vertical as horizontal thrust from the arch is resisted by the tie. Aesthetic improvements can be made through the incorporation of concrete form liners, reveals, stain, and/or other treatments.

The proposed I-35 bridges will likely require deep foundations. Drilled shafts are one of the most common deep foundation types and can also alleviate scour concerns. Driven steel h-piles or pipe piles may also be used. Spacing can be optimized to provide more support under the arch bearings.

4.5 Constructability

4.5.1 Construct In Place

If the alignment can be adequately shifted or traffic can be fully detoured, the arch may be constructed in place. Cantilever construction, where the arch is built from both sides of the span, is most common. This can be achieved using temporary falsework in the river or back stays connected to temporary towers. The latter method requires an economical means of anchoring the back stays and balancing the induced forces.

Tolerances for fabrication and assembly of tied arches are generally tight, but not as stringent as true arches. Hangers often require tensioning at multiple stages of construction and an installation sequence may be required.

FIGURE 17 – ARCH ERECTION ON FALSEWORK (HALSTED BRIDGE)

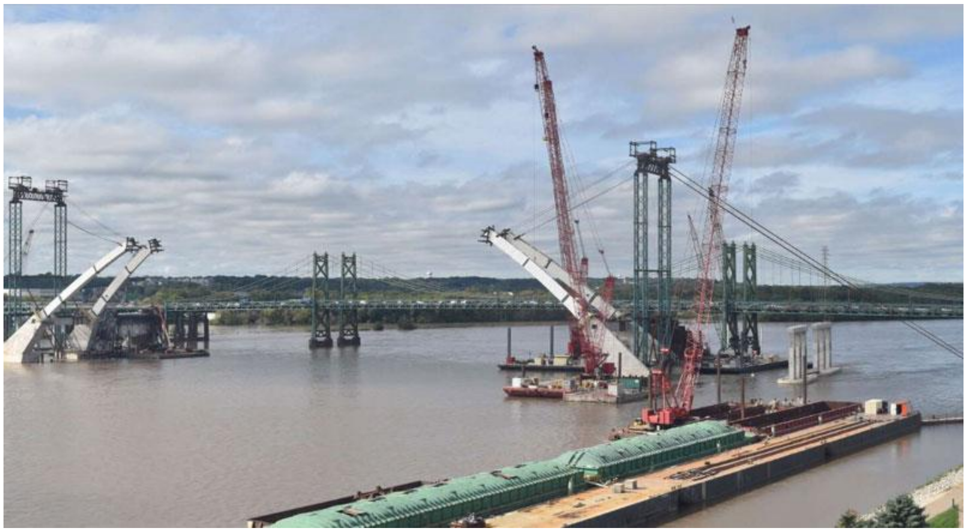


FIGURE 18 – ARCH ERECTION WITH BACK STAYS (I-74)

4.5.2 Float In

The methods used to construct the bridge in place in Section 4.5.1 can also be used to build the superstructure on barges next to the site. Once the superstructure steel is complete, it is floated along the river to the final site and lowered into place. The deck and barriers are typically poured after the steel is supported by the permanent substructure.

FIGURE 19 – FLOAT IN ARCH PLACEMENT (BROADWAY BRIDGE)

4.5.3 Lateral Roll In

Similar to the float in method, the tied arch superstructure may be constructed on temporary bents adjacent to the final alignment. As temporary bents are likely to have more vertical capacity than barges, this may include the deck, barriers, and any other attachments to the bridge. Once the superstructure is ready, rollers are used to move the bridge laterally into position and lower it onto the permanent substructure. The outage window is usually faster than a float in because the only work afterwards consists of inspection, joint installation, and other minor tasks.

FIGURE 20 – LATERAL ROLL IN ARCH PLACEMENT (DEPOT STREET BRIDGE)

4.6 Future Inspection and Maintenance

Future inspection of a tied arch bridge will require access to the top of the arch. The interior of the arch ribs and tie girders may or may not require inspection based on the final details and requirements of the owner. Barges may be used to inspect the underside of the deck and floor system. The tie girders will likely be considered fracture-critical, regardless of whether internal redundancy has been provided. A complex inspection plan should be developed and implemented to address any structure-specific requirements.

Maintenance of a tied arch bridge is consistent with other steel bridge types. Painting is the most common maintenance item, followed by expansion joint and bearing replacements. Hanger replacement is not anticipated but can be facilitated using two strands at each hanger location.

FIGURE 21 – INSPECTION EQUIPMENT FOR UNDERSIDE OF TIED ARCH (HALSTED BRIDGE)

5 CABLE-STAYED

5.1 Structure Description

The bridge deck for a cable-stayed bridge is supported by a series of cables attached directly to tall towers at one or both ends of the span. Back spans with cables are typically used to balance the forces in the tower and create a more efficient structure. Edge girders on either side of the roadway resist the compressive forces induced by the inclination of the cables and are connected to the framing supporting the deck.

5.2 Proposed Geometry

To span the entirety of the Oklahoma River, the main spans of the I-35 SB and NB cable-stayed bridges have been laid out with a span length of approximately 520'. This falls within the feasible span length range for a cable-stayed bridge, and just under the optimal span length range (see **Figure 6**). To efficiently balance the main span, the back span length should typically be between 40% and 60% of the main span length. The proposed back span for the I-35 bridges is 300' in length. In order to keep the hangers at an appropriate incline, the minimum tower height over the deck is approximately 200'.

North of the northernmost cable-stay connection to the deck, the edge girders can be flared to accommodate a variable structure width. This can reduce the superstructure width at the north end of the span as compared to the tied arch option, as the flared girders can partially accommodate the diverging ramp alignments. The NB out-to-out deck width of the proposed cable stayed structure varies from approximately 98' to 103'. The SB out-to-out deck width of the proposed cable-stayed structure varies from approximately 97' to 99'.

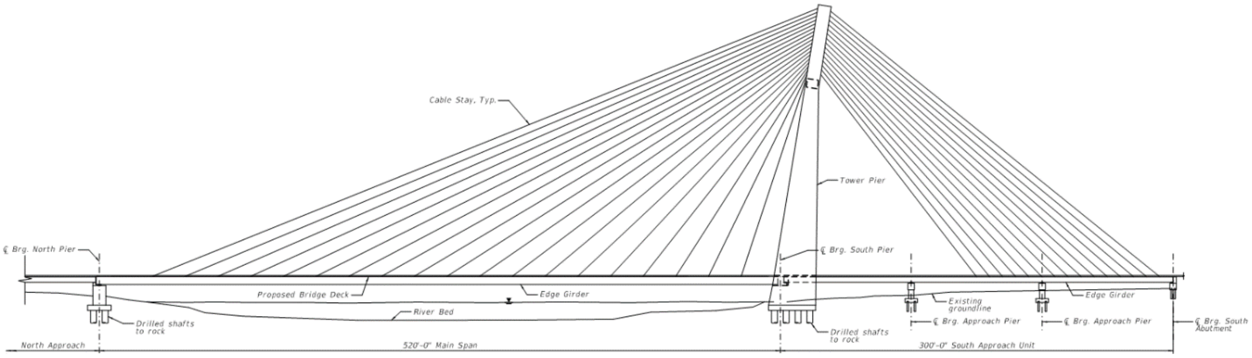


FIGURE 22 – CABLE-STAYED ELEVATION VIEW

5.3 Superstructure

5.3.1 Towers

The demands on the towers are heavily influenced by the span configuration. If a significant load imbalance occurs between the main span and the back span, the tower must resist the load in flexure. There are many ways to reduce this imbalance for dead loads when long back spans are not viable. One method is to take advantage of the weight of the tower itself. By tilting the heavy tower backwards (away from the main span), it imposes bending moments opposite the load imbalance. Alternatively, the back span can be counterweighted. This can involve concrete infill within the superstructure itself or buried cells full of soil or concrete in the approach roadway.

FIGURE 23 – CABLE-STAYED BRIDGE WITH ANGLED TOWER (ERASMUS BRIDGE)

The towers come in various configurations and are often constructed of reinforced concrete with a hollow center for material savings and inspection access. Single column, A-, inverted Y-, and H-towers are all common variants (see Figure 24 – Cable-Stayed Tower Configurations). Single column, A-, and inverted Y-towers share similar cable geometry with stays angled in both planes. This increases the detail complexity for the edge girder anchorage, induces transverse compression forces in the floor system, and may impinge on the clearance envelope of the roadway. Single column towers also resist transverse loads in flexure whereas the A- and inverted Y-towers resist some of the load axially in the legs. H-towers keep the stays in a vertical plane to alleviate the challenges associated with the other shapes but appear more utilitarian.

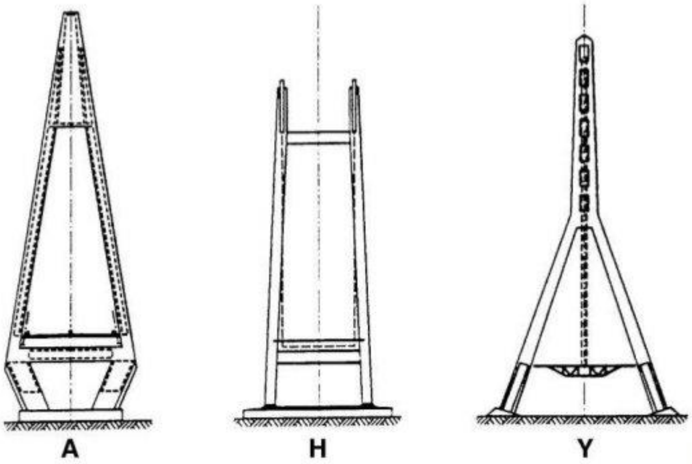


Figure 24 – Cable-Stayed Tower Configurations

5.3.2 Edge Girders

The edge girders run along each side of the deck and are supported by the bottom of the cable stays. They carry the horizontal component of the cable stay loads plus some degree of flexure and shear. The edge girders also frame into the floor system that supports the deck.

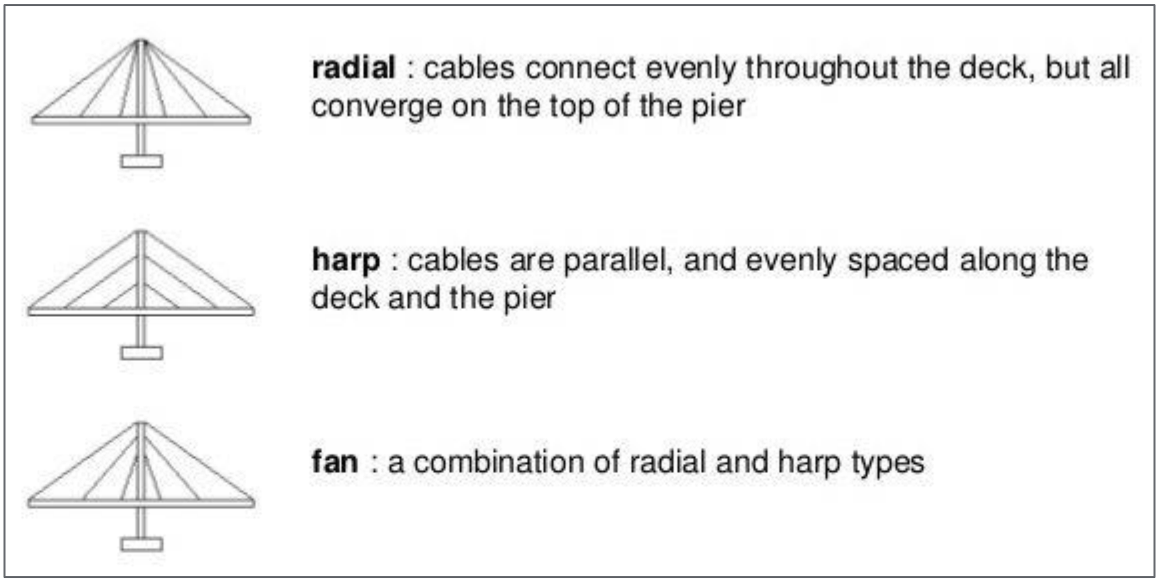
The edge girder is often a box girder or I-section. Unlike tie girders under tension for arches, these girders are under compression and do not have the same internal redundancy considerations. Orthotropic decks have also been used on several cable-stayed bridges, but they tend to be cost-prohibitive on shorter spans.

5.3.3 Cable Stays

The cable stays can be arranged in various patterns to achieve a particular aesthetic or optimize the forces in the tower. The cable inclination angle relative to the deck has a significant effect on the compressive forces in the edge girders and should generally be greater than 22 degrees.

Cable stays are constructed from a series of parallel prestressing strands. Often these are encased in PVC for added corrosion protection. The strands are threaded through anchorages and stressed during construction to achieve the desired loads.

Cable vibrations may be induced by wind loads. Mitigation methods, if required, typically use some type of damper system. Vibration monitoring may be used to determine the need for mitigation and to verify the performance of those measures after installation.



radial : cables connect evenly throughout the deck, but all converge on the top of the pier

harp : cables are parallel, and evenly spaced along the deck and the pier

fan : a combination of radial and harp types

FIGURE 25 – COMMON CABLE STAY LAYOUTS

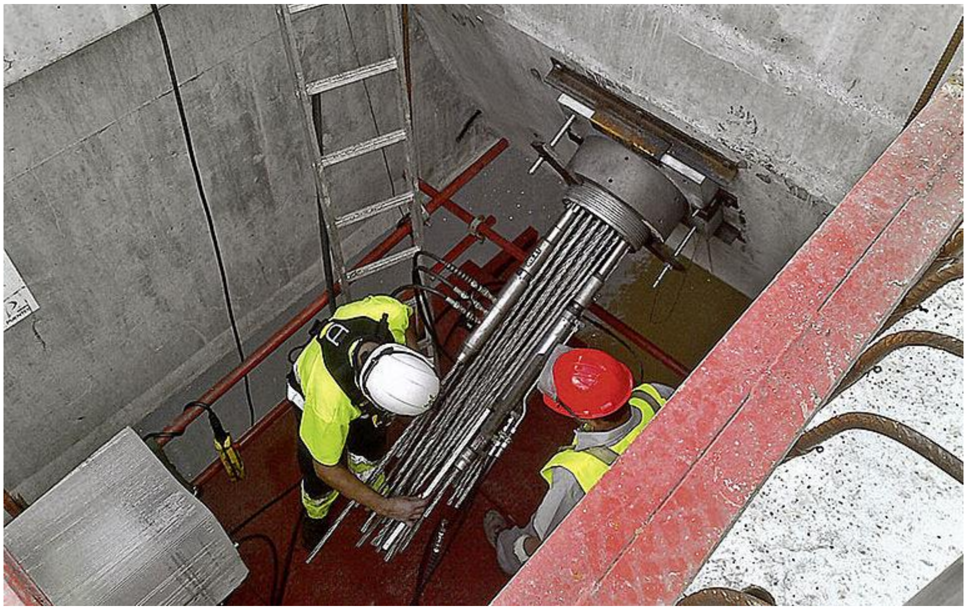


FIGURE 26 – CABLE STAY INSTALLATION

5.3.4 Floor System

The floor system is often comprised of transverse floorbeams spanning between edge girders and longitudinal stringers between floorbeams. The transverse floorbeams tend to be welded plate girders and the web depth can be varied to match the cross section of the roadway. Longitudinal stringer spans are often short enough to make rolled beams viable. Lateral bracing of the floor system is provided to facilitate construction and future deck replacement.

5.4 Substructure

The tower at the level of the bridge deck will support the floor system on both sides. Access to the interior of the tower may be provided with a door at deck or ground level. Aesthetic improvements can be made through the incorporation of concrete form liners, reveals, stain, and/or other treatments.

The proposed I-35 bridges will require deep foundations to resist any unbalanced loading. Drilled shafts are one of the most common deep foundation types and can also alleviate scour concerns. Driven steel h-piles or pipe piles may also be used.

5.5 Constructability

5.5.1 Construct In Place

Unlike arches or trusses that can be constructed off alignment and moved, a cable-stayed bridge must be constructed in place. This can have a significant effect on staging and maintenance of traffic depending on the extent of the alignment shift.

Cable-stayed bridges are traditionally built using the balanced cantilever method of construction. The tower is constructed first, followed by alternating segments of deck on each side. Pairs of cables are attached as each deck segment is erected. This approach allows the cable supported spans to be constructed without additional shoring while minimizing bending forces on the tower.

FIGURE 27 – CABLE-STAYED BRIDGE CONSTRUCTION (TEMBURONG BRIDGE)

5.6 Future Inspection and Maintenance

Future inspection of the cable ends can be performed at deck level and from the inside of the tower. The underside of the deck and floor system should be accessible from barges for this project. A complex inspection plan should be developed and implemented to address any structure specific requirements. Monitoring systems for cable stays are available to monitor structural health, load, and/or vibration.

A maintenance plan should be developed for this type of structure. Common items include painting, expansion joint repair, and bearing replacements. Cable stay protection systems must be kept functional. Cable stay replacement is not anticipated but should be considered in the design.

6 COST ASSESSMENT

The following cost assessment was developed based on a cost per square foot of bridge deck basis, and not on calculated quantities. The estimated cost per square foot for each bridge type is based on previously built/bid projects for both the tied arch and the cable-stayed option. In addition, the unit costs were developed in consideration of factors such as location, material availability/costs in the area, as well as a construction year of 2025.

6.1 Tied Arch Cost Assessment

Bridge Element	Unit Cost Per Sq. Ft.	Area of Bridge Deck (Sq. Ft.)	Total Cost
NB Structure Main Span	$ 1,200	53,500	$ 64.2 M
NB Structure Approach Unit	$ 200	29,200	$ 5.8 M
SB Structure Main Span	$ 1,200	50,600	$ 60.7 M
SB Structure Approach Unit	$ 200	28,700	$ 5.7 M

Subtotal NB Structure:	$ 70.0M
Subtotal SB Structure:	$ 66.4M
Total Cost:	**$ 136.4M**

6.2 Cable Stayed Cost Assessment

Bridge Element	Unit Cost Per Sq. Ft.	Area of Bridge Deck (Sq. Ft.)	Total Cost
NB Structure Main Span	$ 1,700	51,200	$ 87.0 M
NB Structure Approach Unit	$ 850	29,500	$ 25.1 M
SB Structure Main Span	$ 1,700	50,600	$ 86.0 M
SB Structure Approach Unit	$ 850	29,200	$ 24.8 M

Subtotal NB Structure:	$ 112.1 M
Subtotal SB Structure:	$ 110.8 M
Total Cost:	**$ 222.9 M**

7 RECOMMENDATION

Based on the work completed within this long span bridge type study, Benesch would give a preliminary recommendation to advance the tied arch bridge alternative for further evaluation. This recommendation is focused on the initial evaluation of site constraints, cost, and constructability and has been made independent of additional factors that may influence selection of a final bridge type, such as aesthetics, community input, and/or other stakeholder preferences.

8 REFERENCES

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Figure 24 - https://www.infrastructurepc.com/analysis-design-of-cable-stayed-bridge/

Figure 25 - https://www.infrastructurepc.com/analysis-design-of-cable-stayed-bridge/

Figure 26 - https://www.dywidag-formties.com/projects/2013-info-21/relief-for-noia-new-stay-cable-bridge-ensures-summer-months-without-traffic-jams/

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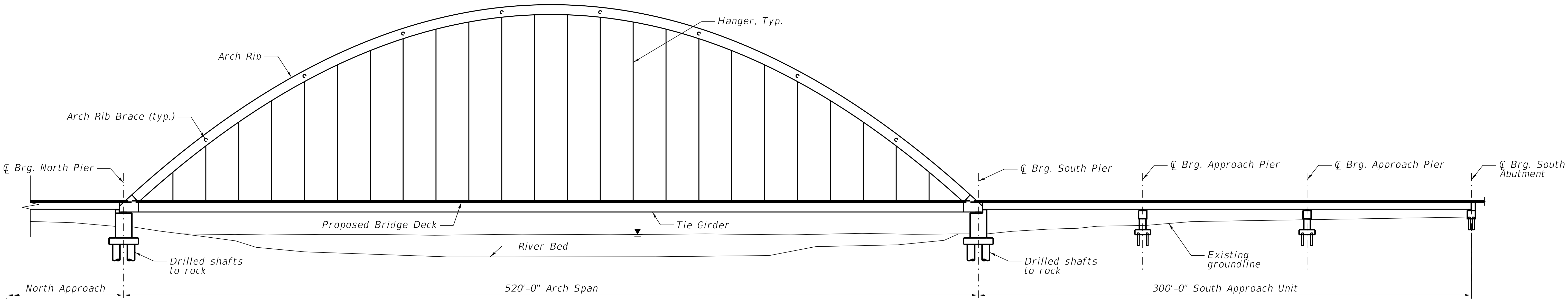
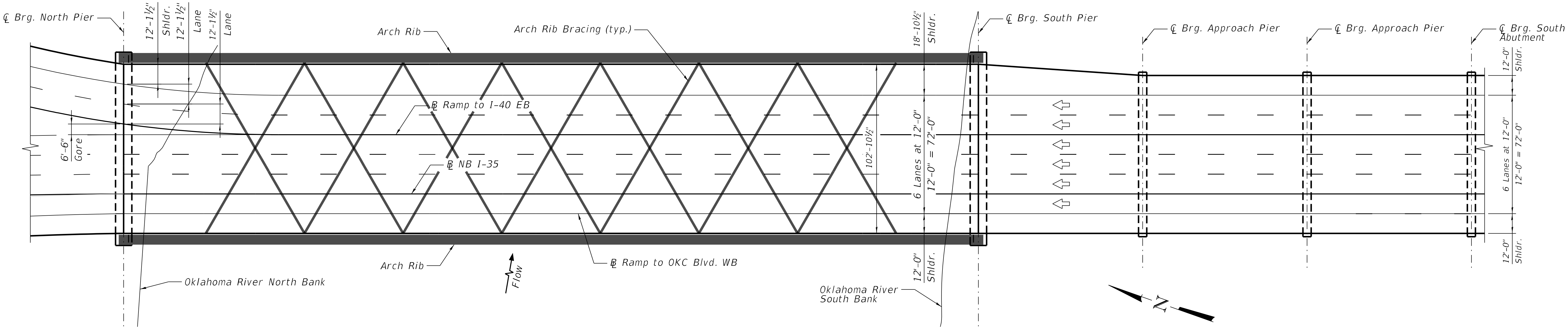
9 INITIAL PLANS, ELEVATIONS, & SECTION VIEWS



ELEVATION



PLAN

NOTE:

Limits of bridge type study do not include north and south approaches to the signature river span. South approach is included for reference only to facilitate comparision to the Cable-Stayed bridge alternative.

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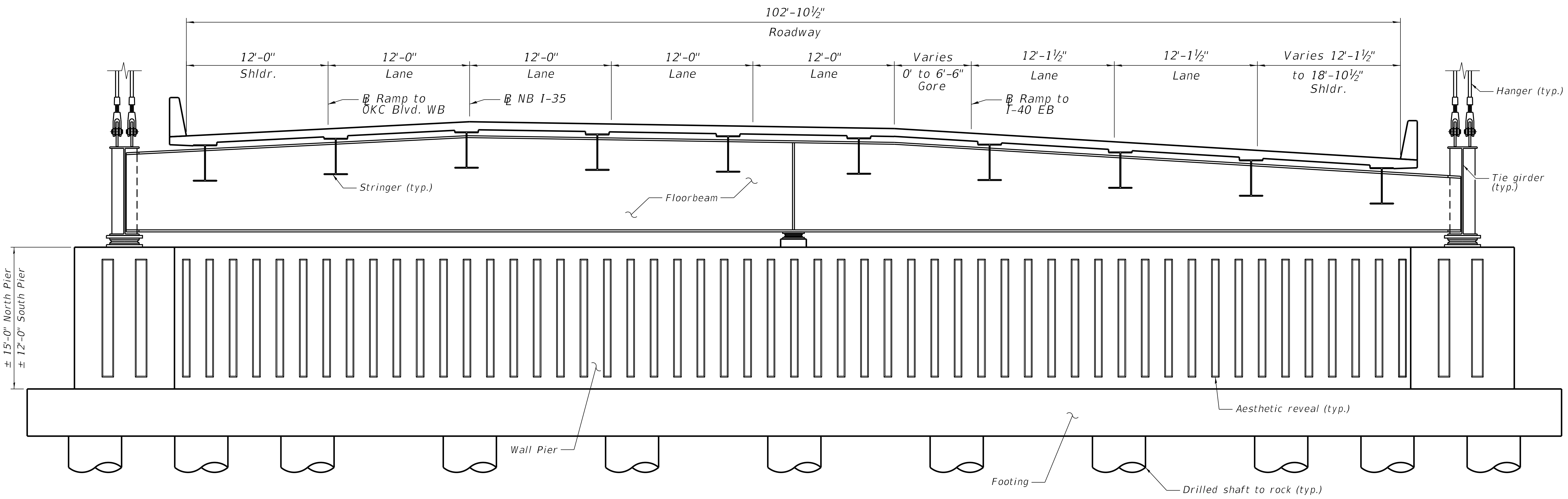
I-35 DALLAS JUNCTION TIED ARCH CONCEPT (1 OF 5)
NORTHBOUND ARCH GENERAL PLAN & ELEVATION



SECTION AT PIER

(Looking north)

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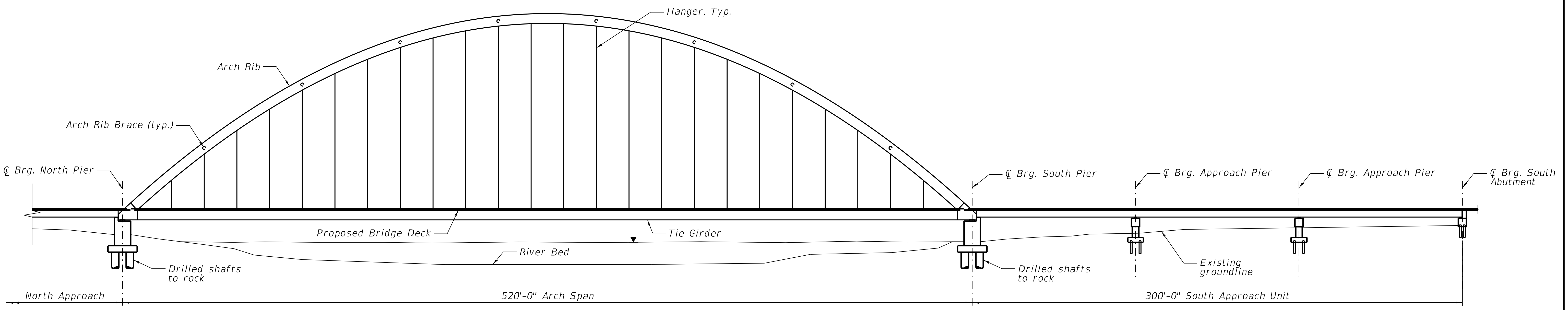
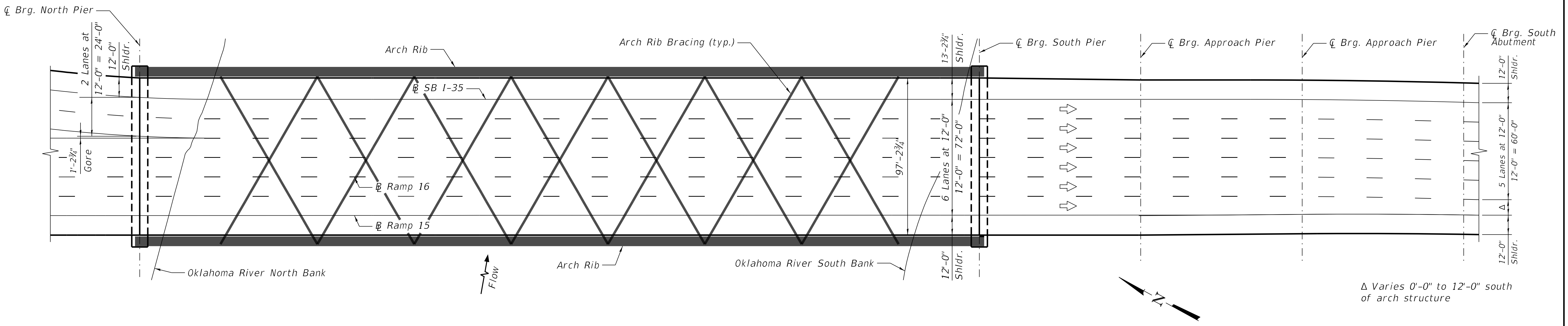
I-35 DALLAS JUNCTION TIED ARCH CONCEPT (2 OF 5)
NORTHBOUND CROSS SECTION



ELEVATION



Δ Varies 0'-0" to 12'-0" south of arch structure

PLAN

NOTE:

Limits of bridge type study do not include north and south approaches to the signature river span. South approach is included for reference only to facilitate comparision to the Cable-Stayed bridge alternative.

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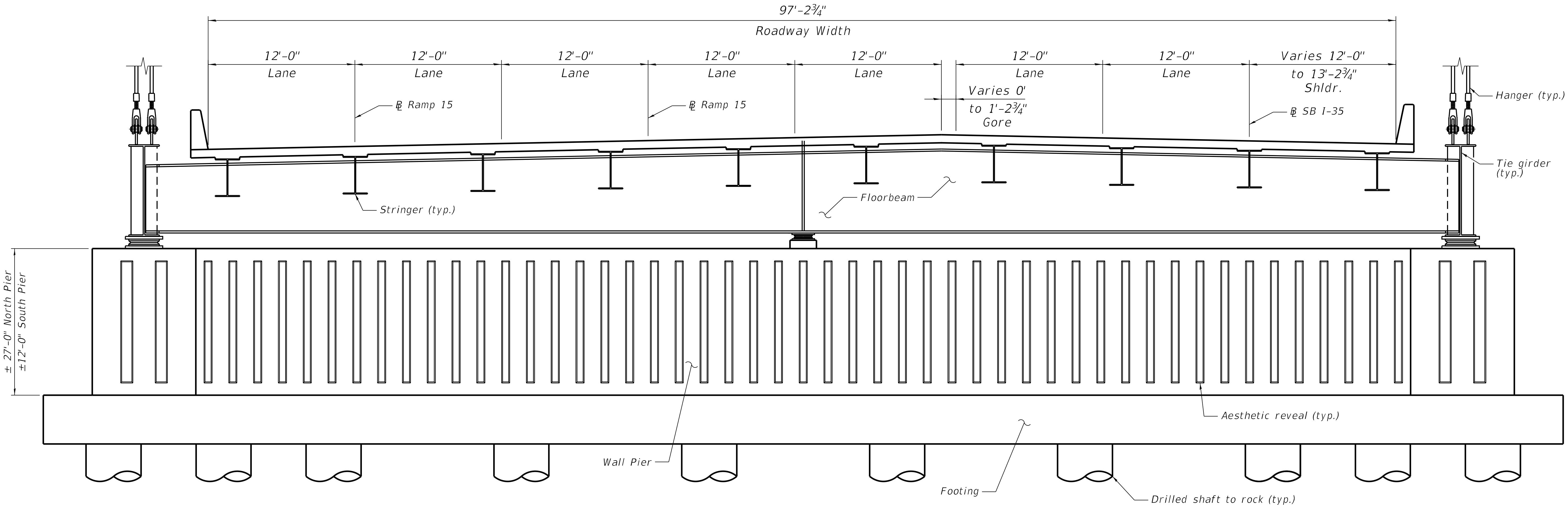
I-35 DALLAS JUNCTION TIED ARCH CONCEPT (3 OF 5)
SOUTHBOUND ARCH GENERAL PLAN & ELEVATION



SECTION AT PIER
(Looking north)

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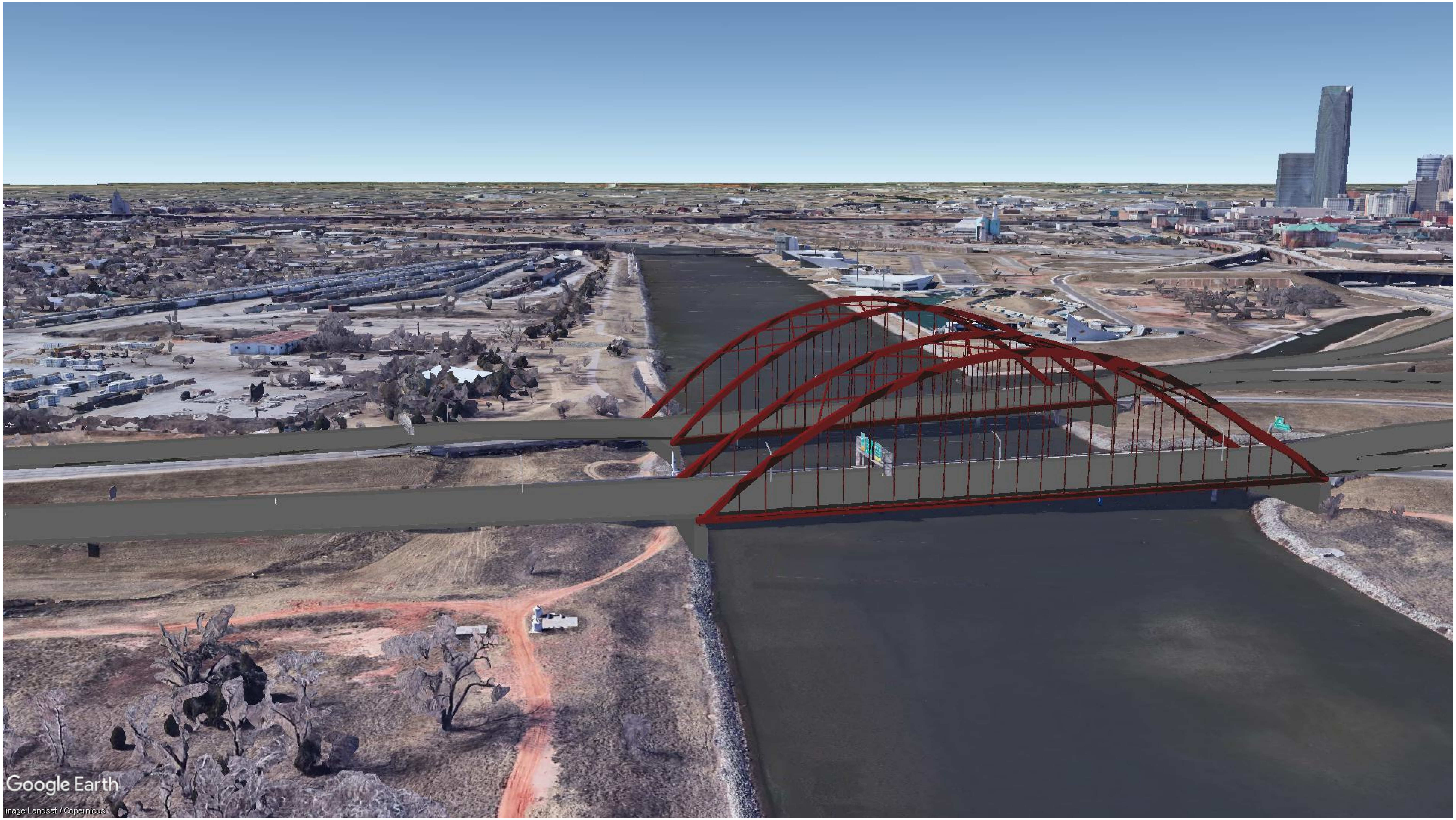
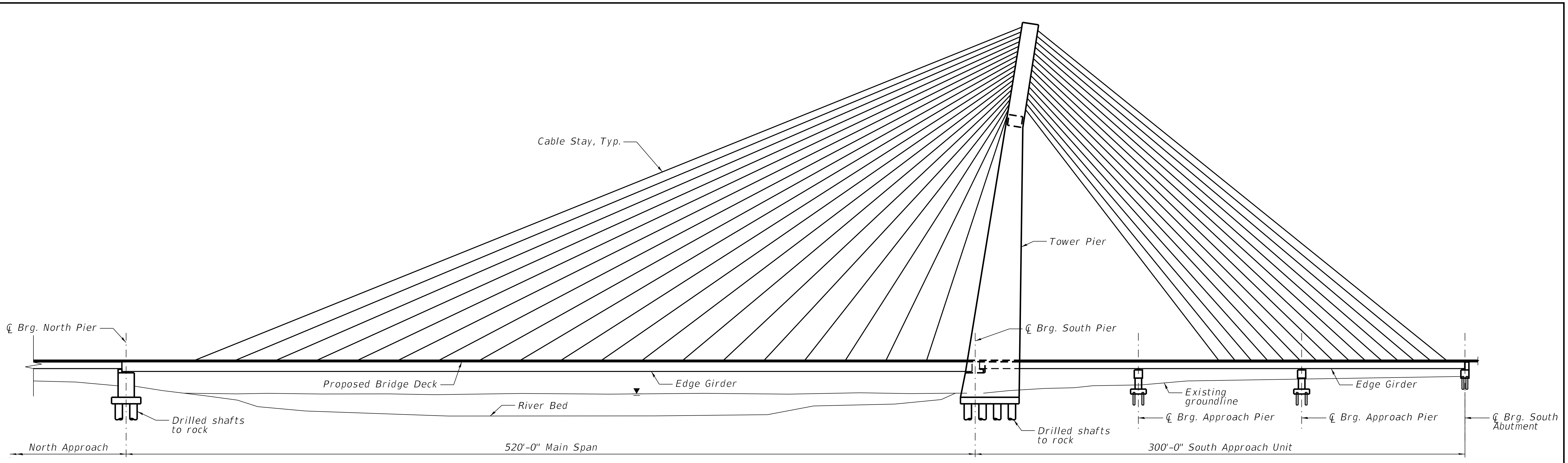
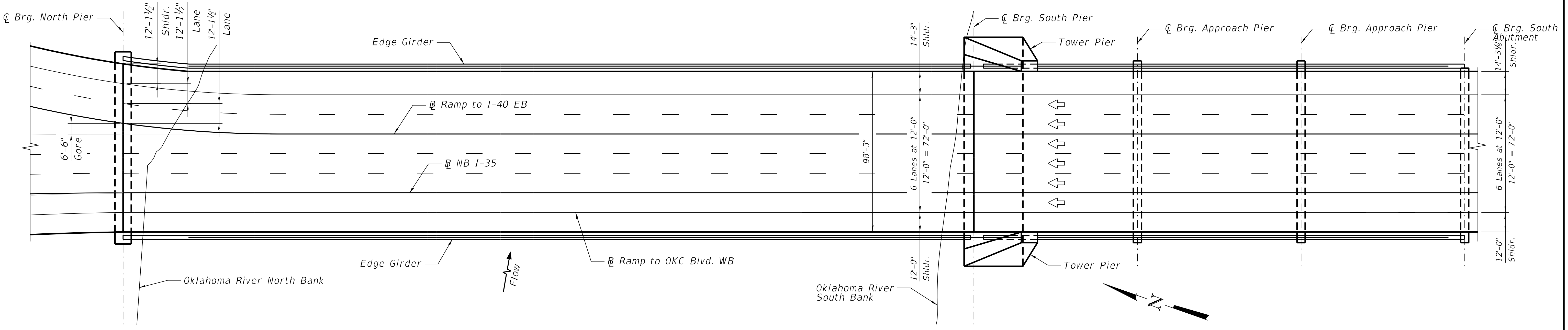
I-35 DALLAS JUNCTION TIED ARCH CONCEPT (4 OF 5)
SOUTHBOUND CROSS SECTION



I-35 DALLAS JUNCTION TIED ARCH CONCEPT (5 OF 5)
NORTHBOUND AND SOUTHBOUND ARCHES CONCEPT RENDERING



ELEVATION



PLAN

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Limits of bridge type study do not include north and south approaches to the signature river span.

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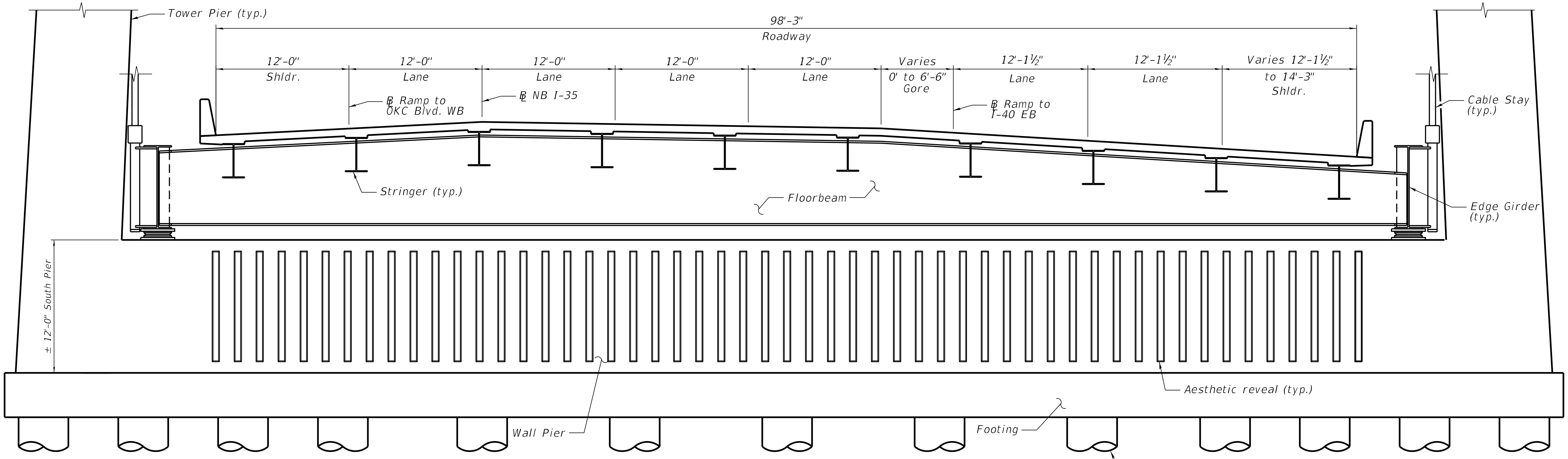
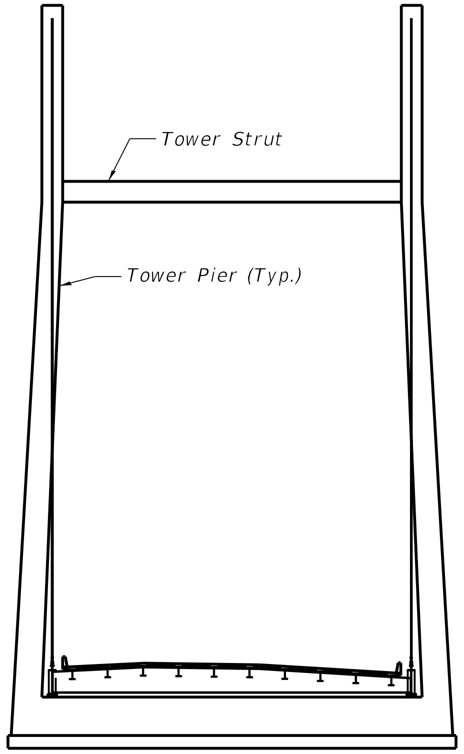
I-35 DALLAS JUNCTION CABLE-STAYED CONCEPT (1 OF 4)
NORTHBOUND GENERAL PLAN & ELEVATION



SECTION AT PIER
(Looking north)



SECTION AT TOWER PIER

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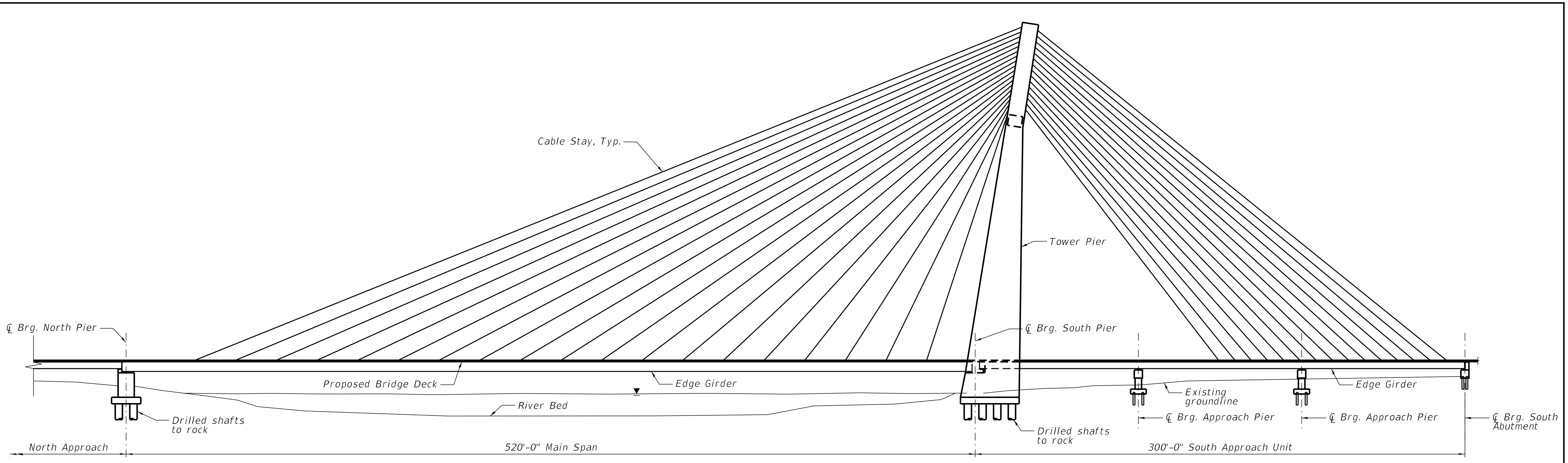
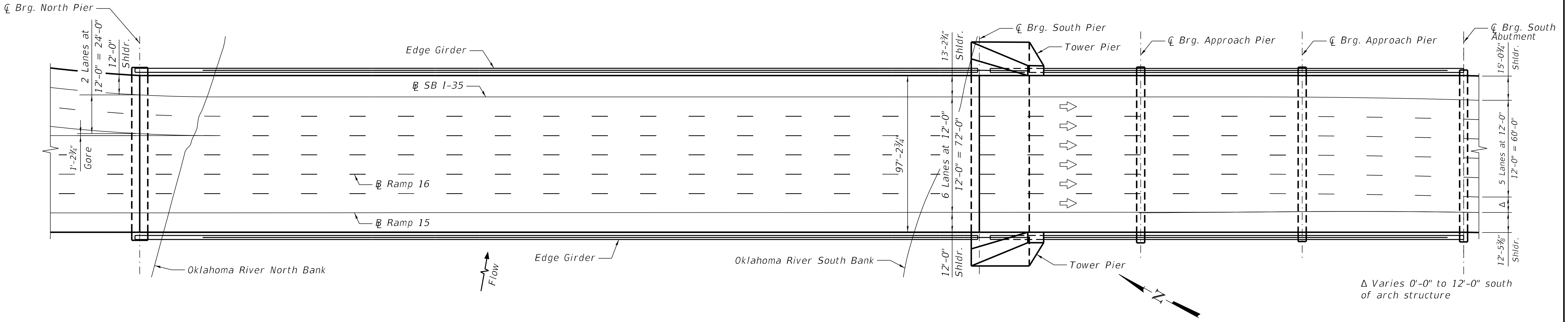
I-35 DALLAS JUNCTION CABLE-STAYED CONCEPT (2 OF 4)
NORTHBOUND CROSS SECTION



ELEVATION



Δ Varies 0'-0" to 12'-0" south of arch structure

PLAN

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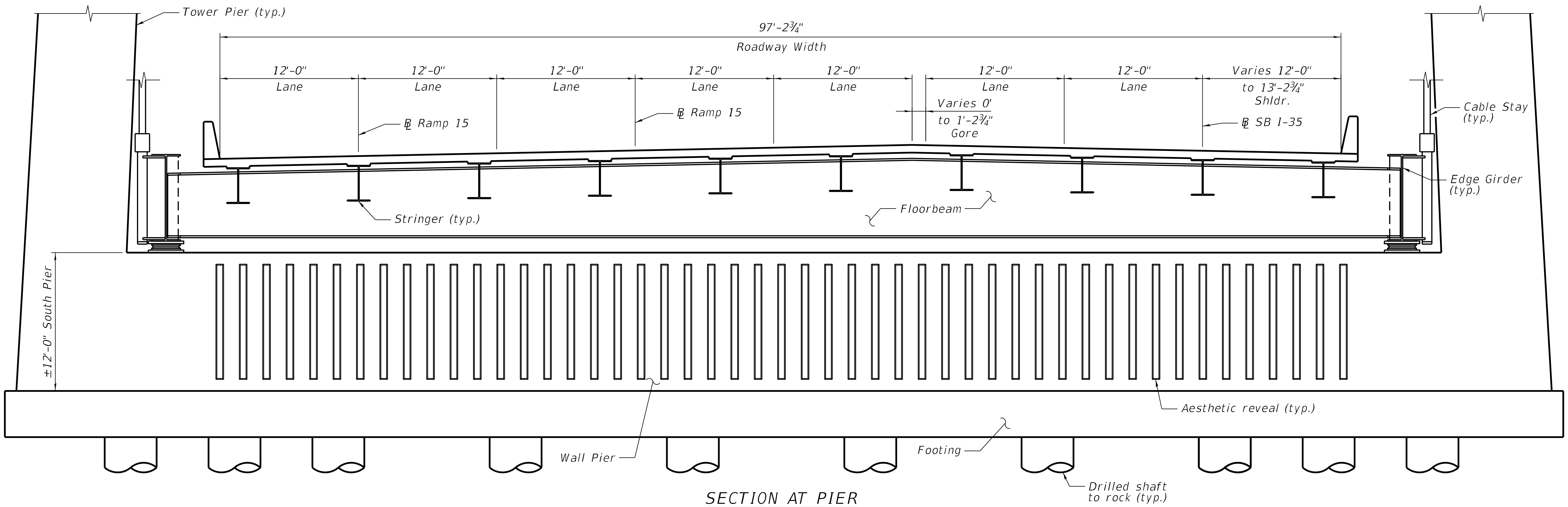
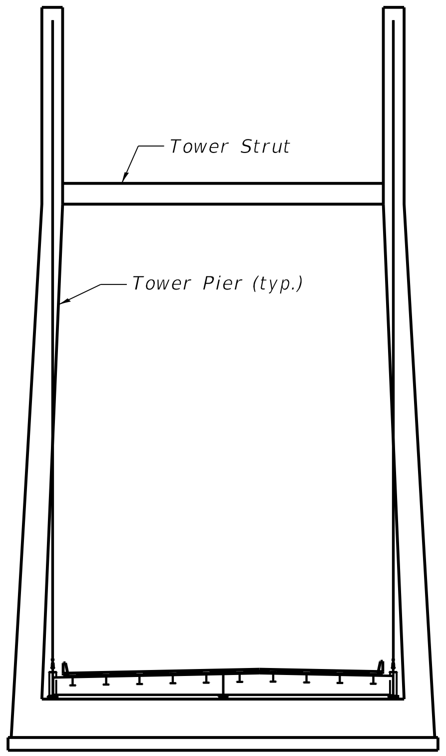
I-35 DALLAS JUNCTION CABLE-STAYED CONCEPT (3 OF 4)
SOUTHBOUND GENERAL PLAN & ELEVATION



SECTION AT PIER

(Looking north)



SECTION AT TOWER PIER

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I-35 DALLAS JUNCTION CABLE-STAYED CONCEPT (4 OF 4)
SOUTHBOUND CROSS SECTION