HOV Bridges Hurdle Obstacles; Including Their Own Substructure

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ABSTRACT

Dual HOV ramp bridges (1998'-long SB and 1872'-long NB) connect Arizona's SR51 Piestewa Freeway and SR101L Pima Freeway. These bridges employ 132 precast/prestressed concrete girders for quick, safe, and cost effective bridge construction. Precast concrete is also used because extensive falsework or fill cannot be placed in the Bureau of Reclamation Reach 11 Flood Control Basin, over which these bridges pass.

The SB Bridge has 17 spans – 11@126' and 6@102'. The NB Bridge has 16 spans – 10@126' and 6@102'. The dual bridges (almost entirely curved and 5.5% superelevated) pass under the existing Ramp NW1 Bridge, then over SR101L EB lanes. Dual SB/NB bridges are used for two key reasons. Separate bridges facilitate 1-column piers that can be staggered for optimum independent placement. Separate bridges have only 4 girder lines for smaller pier loads – critical where three straddle bents, spanning SR101L EB, carry the bridge loads.

Staggered piers are essential for constructability of Spans 2S and 1N. One abutment and three piers are carefully situated outside the "shadow" of existing Ramp NW1 Bridge for drilling rig mast clearance, and girder erection crane rigging clearance. Staggered piers (and the surprisingly fundamental span arrangement) situate four piers fairly close to SR101L EB, thus, making 126' (Type 6) and 102' (Type 4) spans feasible with only three straddle bents.

Straddle Bents are commonly used for severe skew crossings. Design and construction are greatly simplified by having three 90' straddles all radial, level, and essentially identical. Just the SB Bridge is supported by a stepped pedestal atop Straddle Bent 10S, while the NB Bridge passes over – clear by 8 inches. Similarly, just the NB Bridge is supported by stepped pedestals atop Straddle Bents 10N & 11N, while the SB Bridge passes over – clear by over 18 inches. This clever separation technique is the first of its kind in Arizona.

Keywords: Arizona Department of Transportation, SR51, Piestewa Freeway, SR101L, Pima Freeway, Bureau of Reclamation (BOR), Reach 11 Basin, Post-tensioned, Straddle bents, Innovation, Stanley.

ABBREVIATIONS AND NOMENCLATURE

AASHTO	American Association of State Highway and Transportation Officials
ADOT	Arizona Department of Transportation
BOR	Bureau of Reclamation
CAP	Central Arizona Project
EB	Eastbound
ES	Eastbound-to-Southbound
HOV	High Occupancy Vehicle ("carpool")
LT	Left, or offset left
NB	Northbound
NE	Northbound-to-Eastbound
NW	Northbound-to-Westbound
RCBC	Reinforced Concrete Box Culvert
ROW	Right-Of-Way
RT	Right, or offset right
SB	Southbound
SRxx	State Route xx
SRxxxL	State Route xxx Loop
WB	Westbound
WS	Westbound-to-Southbound

Figure 01 – First of such applications in Arizona, straddle bents support only one-of-two bridges passing over them. Pedestals constructed atop the straddle bents transfer just one superstructure load to the substructure – the other superstructure does not touch. Straddle bent Pier 10S (foreground) carries the HOV SB Bridge (LT) – but not the HOV NB Bridge (RT); Pier 10N and Pier 11N (beyond) support only the HOV NB Bridge.

INTRODUCTION

For over two decades, the Arizona Department of Transportation (ADOT) has been engaged in building a Regional Freeway System (RFS) for the metropolitan Phoenix area. All of the initially programmed and funded freeways will be complete and open to traffic by the end of Summer 2008. Additional expansion and improvements to the RFS are planned for the next twenty years.

Throughout the initial 20-year program, ADOT wisely considered divided highways with an open median to accommodate future General Use and future High Occupancy Vehicle (HOV) lanes wherever practicable. That future is now.

State Route 51 (SR51) Piestewa Freeway is a north-south corridor about sixteen miles long. It is the only freeway passage through the Phoenix Mountain Preserve, connecting north Phoenix, Scottsdale, and Paradise Valley to the downtown Phoenix area. Originally called the Squaw Peak Parkway, the southern six miles (from the I-10/SR51/SR202L freeway system interchange to about Glendale Avenue) were started by the City of Phoenix during the late 1980's. ADOT assumed control over design and construction to complete the freeway between 1991 and 2003, and immediately thereafter commenced the addition of the "future lanes".

The southern part of the freeway passes through dense residential and commercial areas. Some portions are depressed one level below grade, incised between flanking retaining walls. Even the at-grade and above-grade portions face right-of-way restrictions on both sides. Nonetheless, about 9.5 miles of HOV lanes, one SB and one NB, were shoe-horned into the narrow, constrained corridor via an $80-million Design-Build project in 2003-2004. The Design-Build contract included HOV direct connections to I-10.

The northern part of the freeway corridor is wider. It passes through the Phoenix Mountain Preserve and extends north to connect with the SR101L Pima Freeway – a TEE freeway-to-freeway system interchange. ADOT built the northern part with an open median to accommodate median in-fill construction and HOV lanes.

One HOV lane connects SR101L westbound to SR51 southbound (for A.M. peak inbound traffic) and one HOV lane connects SR51 northbound to SR101L eastbound (for P.M. peak outbound traffic). For simplicity the inbound WB-to-SB movement is called SB, or "S"; and the outbound NB-to-EB movement is called NB or "N". Conceptual horizontal and vertical alignment provisions for a connector bridge, the subject of this paper, were also included in the original interchange design.

Under an aggressive accelerated schedule, the HOV lane completion Final Design was completed between Spring 2006 and Winter 2006. Currently underway, the construction project duration is from Summer 2007 to Fall 2008.

Figure 02 – The HOV lane project includes 6 miles of SR51 and 1 mile of SR101L. Source: http://www.azdot.gov/Highways/valley_freeways/SR51/Images/SR51HOVFull.jpg

CONSTRAINTS UPON CONSTRAINTS

The conceptual horizontal and vertical alignments were established to be compatible with numerous constraints. Like most HOV ramps, the alignment starts in the median of one freeway, threads its way through general directional ramps and ends in the median of the other freeway. These HOV ramps can be called fly-over/under/above/over ramps because they start in the median of SR51 near the north bank of the Central Arizona Project (CAP) Canal; pass over the Reach 11 Low Flow Channel; under an existing span of the Ramp NW bridge; above a Reach 11 Flood Control Basin; over the SR101L Pima Freeway eastbound lanes; and end in the median of SR101L.

The 336-mile long CAP Canal delivers fresh water from Lake Havasu on the Arizona/California border to Phoenix and Tucson. Reach 11 has a series of major flood control storage basins, within which the *City of Phoenix Reach 11 Recreation Area* has been developed. Critical to the Bureau of Reclamation and the Flood Control District of Maricopa County, the basins have a specific storage volume that cannot be adversely compromised. For every cubic yard of new infrastructure added to the Basin a compensatory cubic yard of storage volume must be restored elsewhere. A precast concrete solution was mandatory because extensive falsework needed for cast-in-place construction was not permitted. Numerous Reach 11 "sub-basins" are interconnected at the Reach 11 Low Flow Channel.

Figure 03 – Just beyond the north levee of the CAP Canal, one 472' bridge carries SR51 HOV (SB & NB) over the Low Flow Channel of the Reach 11 Basin. At left, Ramps ES & WS merge into SR51 SB; at right NB SR51 diverges into Ramps NW & NE.

The HOV ramp faces even more constraints. From a nearby electrical substation in the southeast quadrant, one set of overhead power lines head west over SR51 and another set of overhead power lines head north over SR101L. Storm water intercepted along the north side of SR101L passes under the freeway through a large reinforced concrete box culvert to the Reach 11 Flood Control Basin.

ORIGINAL DESIGN CONCEPT

The HOV ramp carries one lane each way. The initial HOV bridge design concept called for one (two-way) bridge about 62 feet wide and 3,620 feet long. The span arrangement was as follows:

116’+120’+118’+113’+73’+(28*110’) = 3,620’

The first four spans were skewed about 17° RT and had piers with three cylindrical columns to match existing SR51 Low Flow Channel Bridges. The 73’ span was a transition span from 17° RT skew to zero skew. The 28 repetitive spans comprised the rest of the long bridge and had large double-cantilever “hammerhead” piers, except at two locations where straddle bents were needed to cross SR202L EB lanes. Expansion joint locations were not specified.

The original design concept was simple, straightforward, and it satisfied stakeholder criteria. But it was very expensive and had a few unresolved constructability issues.

Beyond the four spans crossing the Low Flow Channel, the profile was very close to the existing ground line. The deck and the girders were above grade, but the bottom of several pier caps was partially embedded into existing ground. Excavation was neither practical nor possible because the affected areas were part of the roadway prism embankment for the adjacent ramp.

One of the large hammerhead piers was situated directly beneath the existing Ramp NW Bridge. Geotechnical criteria required foundations to consist of drilled shafts but the headroom in the shadow of the existing bridge was insufficient for the drill rig mast height. The same limited headroom did not facilitate common cranes needed to set the supported back-span and ahead-span precast prestressed concrete girders.

FINAL DESIGN CONCEPT – FIVE MAJOR ENHANCEMENTS

Five noteworthy revisions were made to the original design concept to reduce cost, enhance the bridge layout, and eliminate constructability hindrances. All five modifications were identified while pursuing the Final Design contract, and all five modifications are incorporated in the Final Design plans.

Eliminate 1,277’ of unnecessary bridge – Where the profile was very close to the ground, about 78,100 square feet of bridge deck area were eliminated and replaced by roadway. This created two distinct bridge sites – one for the Low Flow Channel and one for the remainder. Acceptance of this drastic change required the calculation of the volume of roadway embankment being placed in the flood control basin below Elevation 1552 (reducing storm water storage capacity), and approval from the BOR and CAP jurisdictional agencies that offsetting storage compensation could be provided elsewhere within the Reach 11 basins – and still gravity drain.

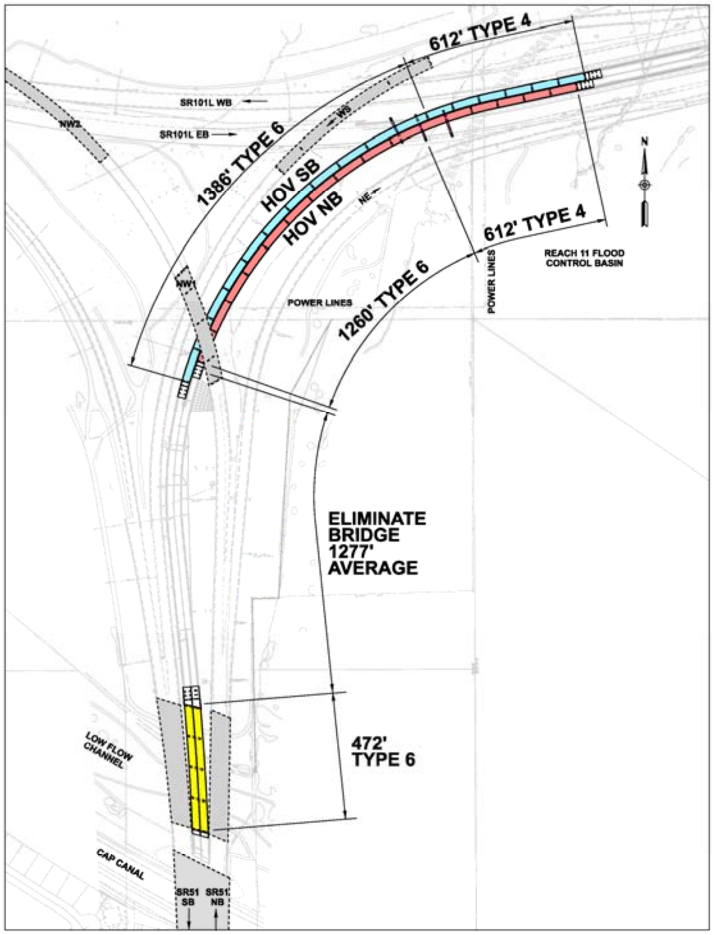

Figure 04 – Cost savings estimated at $5.5-million was achieved by eliminating over 80,000 square feet of bridge.

Single bridge versus dual bridges – The Low Flow Channel Bridge is a single structure. By lengthening about 5 feet, the span arrangement is simplified to [118'+118'+118'+118'] = 472' and all 28 girders are essentially identical. Three cylindrical columns from the original design concept are replaced by two cylindrical columns, slightly larger. The skew matches the adjacent bridges. Further discussion of the separate Low Flow Channel Bridge details is omitted from this article.

The remainder of the HOV ramp, however, has dual structures. The SB direction is shifted one foot left and the NB direction is shifted one foot right to create independent structures. The median "full barrier" is replaced by two "half barriers" separated by about one foot. The key advantage of this revision is to allow independent fine-tuned span arrangement and smaller hammerhead piers.

Figure 05 – Looking east, dual bridges (separated by a 10" gap) carry HOV SB and HOV NB separately under Ramp NW, above the Reach 11 flood control basin, and over SR101L EB. Note, at left, SR101L EB is shifted to a detour and, at center, the overhead power lines' constraints.

Staggered stationing for piers – The dual bridge span arrangements are strikingly similar and very simple, as a result of extensive trial-and-adjust layouts. The shorter NB bridge has ten 126' spans followed by six 102' spans. The longer SB bridge has eleven 126' spans followed by six 102' spans – i.e., it has one more 126' span at the beginning. The SB bridge begins 88' before the NB bridge. This creates an extremely important 38' stagger at all the piers. The stagger increases the distance between drilled shafts and alleviates undesirable capacity reductions caused by "group action" proximity effects. The 38' stagger yields two more major improvements.

Figure 06 – Looking northeast, abutment (foreground) and piers for dual bridges are staggered 38’ for independent fine-tuned placement.

<u>Move piers out from under existing Ramp NW Bridge</u> – The 38’ stagger is just the right amount to shift the abutments and piers for the SB and NB bridges out from the existing bridge’s shadow. Bridge designers coordinated with local foundation shaft drillers to ensure that adequate drill rig mast clearance exists. The designers also coordinated with local precast girder erectors to ensure that girders for SB Span 2 and NB Span 1 could be placed in close quarters – with adequate room for delivery trucks and erection cranes at both ends. There are 28 single column hammerhead piers that have the same size and shape – adjusted only for different cross slope and girder depth.

Figure 07A and 07B – Looking north, HOV SB and NB Bridges pass under the existing Ramp NW Bridge with limited headroom. Final Design bridge layouts move all piers and foundations out from under the shadow of the existing bridge.

<u>Straddles over SR101L EB</u> – It was inevitable that straddle bents were needed to cross the freeway eastbound lanes to get into the median. The SR101L EB crossing includes freeway median widening to add the EB HOV "through"-lane plus transitions. The original design concept showed two large straddle bents – each one carrying the wide two-way bridge. The Final Design concept uses three straddle bents – Pier 10S, Pier 10N, and Pier 11N.

As suggested by the nomenclature, Pier 10S supports only the SB bridge and Piers 10N and 11N support only the NB bridge. The 38' stagger is just right to setup single column piers close to SR101L EB, for both bridges, before and after the straddle bents. It also provides a design benefit of spacing the foundations of the three straddle bents roughly one station apart.

Figure 08 – Looking north, the three straddle bents at (from LT to RT) Piers 10S, 10N, and 11N are level, zero-skew, and essentially identical. Additional constraints under and over SR101L are, at center, large RCBC (outlet visible) and, at right, overhead power lines.

The SB bridge rests on a pedestal at Pier 10S, but hurdles over the Pier 10N and Pier 11N straddle bents without touching. Likewise, the NB bridge rests on pedestals at Pier 10N and Pier 11N, but hurdles over the Pier 10S straddle bent without touching. Consequently, the straddle bent and drilled shaft loads are smaller because they carry only one of the two bridges. This clever separation technique has not been used in Arizona before.

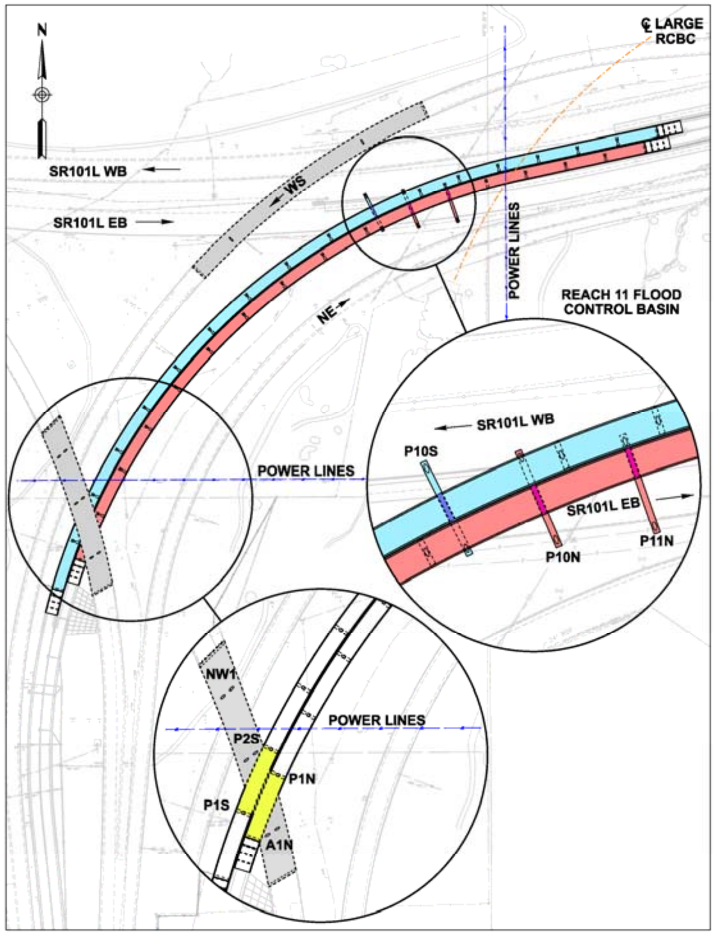

Figure 09 – Of the many constraints, perhaps the top two are (1) passage under existing Ramp NW bridge with no substructure underneath; and (2) passage over SR101L EB with three cleverly designed straddle bents.

COST SAVINGS – ESTIMATED $5.5-MILLION

The original design concept had an estimated cost of $18.292-Million for the long flyover bridge and walls. The 2005 cost estimate was based on a unit bridge cost of $75 per square foot. The 2006 Final Design pay items, unit costs, and quantities gives a unit bridge cost of $80 per square foot. Applying the more recent unit bridge cost, the original design concept estimated price tag goes up to $19.476-Million.

The Final Design engineer's estimate for the Low Flow Channel Bridge and the dual HOV SB and NB bridges and walls was $12.725-Million. This yields a gross savings of $6.751-Million. Since there is cost associated with build the roadway between the bridges, the estimate net savings is **$5.506-Million**.

The Final Design engineer's estimate was validated by the construction bids. The successful Contractor's bid tabulation for bridges and walls is $12.369-Million – less than 3% deviation from the Engineer's estimate.

PRECAST GIRDERS – 132 GIRDERS; JUST TWO TYPES

Girder casting lengths vary slightly due to the horizontal curvature. Nonetheless the design is simplified because the total 132 girders comprise just two groups – 84 AASHTO Type 6 girders for the 126' spans and 48 AASHTO Type 4 girders for the 102' spans. There is one girder depth transition (18 inch step) on each bridge, occurring at an expansion joint.

The SB bridge girder depth transition occurs at Pier 11S, a standard 1-column hammerhead pier. Four beam pockets, 18" deep and 32" wide, are notched into the cap beam to receive the bottom flanges of the deeper Type 6 girders on the back-station side.

Figure 10 – Where the 126' spans and 102' spans adjoin, beam pockets receive the bottom flanges of the deeper back-station girders. Hammerhead Pier 11S shown, pedestal for straddle bent Pier 10N similar.

The NB bridge girder depth transition occurs at Pier 10N, one of the 2-column straddle bents. Similarly, four beam pockets, 18” deep and 32” wide are notched into the “riser” pedestal to receive the bottom flanges of the deeper Type 6 girders on the back-station side.

STRADDLE BENTS – 3 LOCATIONS, PRACTICALLY IDENTICAL

All three straddle bents have the same size and shape – they are 105’ long (90’ center-to-center of columns), 6.5’ wide, and 8.5’ deep. They are all perpendicular to the bridge and cast horizontal/level. All three have twelve post-tensioning ducts, parabolically draped, in a 3V:4H rectangular array. The stepped pedestal shape/size/location, post-tensioned prestress, and rebar stirrup spacing are uniquely designed to satisfy each straddle bent’s geometric, flexural, and shear strength requirements, respectively. The following table summarizes the differences:

Straddle Bent	Supported Spans	Load Application	Strands Per Duct	Total Jacking Force
10S	126’+126’	Centered	25	13,182 K
10N	126’+102’	Centered	22	11,600 K
11N	102’+102’	Off-Center	20	10,546 K

Post-tensioning is applied in two Stages. Stage 1 is applied to offset self-weight and to carry pedestals, girders, and pier diaphragms. Stage 2 is applied to offset the aforementioned plus intermediate diaphragms, deck, barrier, and live load.

Figure 11 – Looking west, straddle bent Pier 10S supports only the HOV SB Bridge (right) while the HOV NB Bridge (left) hurdles over, clear by about 8”.

BRIDGE FRAMES – PLACEMENT OF EXPANSION JOINTS

In Arizona, long precast concrete bridges are subdivided into bridge frames so that strip seal joints can accommodate expansion and contraction. These bridges, 1998’ and 1872’ long, are subdivided into six bridge frames SB and five bridge frames NB. During most of the design process, the frames were envisioned as [3-span] and [4-span] frames as follows:

SB = [3 @ 126’] + [3 @ 126’] + [3 @ 126’] + [2 @ 126’] + [3 @ 102’] + [3 @ 102’]

NB = [3 @ 126’] + [3 @ 126’] + [4 @ 126’] +[3 @ 102’] + [3 @ 102’]

As design progressed and an SR101L EB freeway traffic detour was more closely examined, it was deemed advantageous to move one expansion joint near the end of the NB bridge 102’ west as follows:

NB = [3 @ 126’] + [3 @ 126’] + [4 @ 126’] + [**2** @ 102’] + [**4** @ 102’]

Shortly after the construction contract was awarded, a partnering effort among ADOT, the Designer, and the Contractor ensued and led to a traffic detour plan modification. The well-intended expansion joint shift became unnecessary, but the short 2-span frame remained as-is because the long lead-time bearing pads and strip seal joints were already approved and procured.

CONSTRUCTION – SHIFTED EXPANSION JOINT FOUND USEFUL

An unforeseen underground conflict detected during foundation staking forced designers to revise Pier 12N – the pier to which the aforementioned expansion joint location was shifted. A simple and fast resolution to the interference was developed by the designer, approved by ADOT, and constructed by the Contractor.

The redesigned pier has the drilled shaft and column location offset left slightly with an eccentric cantilever pier cap. The drilled shaft diameter and reinforcing steel increased and column reinforcing steel had to be adjusted accordingly. The unbalanced cantilever pier cap, perhaps a first in Arizona, albeit unintended, blends in well. The expansion joint allows superstructure movement at this location where the unbalanced cantilever pier cap stiffness might be slightly different.

Figure 12 – To clear an underground conflict, Pier 12N was redesigned as unbalanced cantilever to shift the drilled shaft and column.

PRECAST GIRDER PLACEMENT – THREE SETTINGS, THREE SUCCESSES

The 132 girders were erected in three mobilizations per traffic/detour, crane size and access, and Contractor preference as follows:

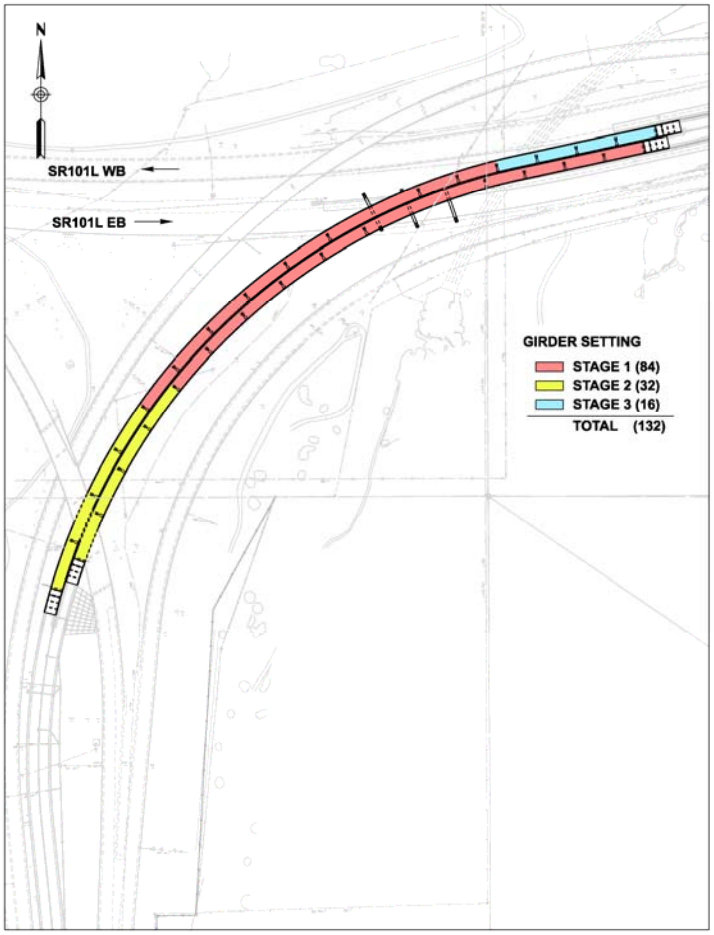

Figure 13 – 132 Girders set in three mobilizations.

The first 84 girders (52 Type 6 and 32 Type 4) were placed while SR202L EB traffic was detoured to the north, sharing part of the SR202L WB alignment. This allowed the Contractor to proceed with stay-in-place steel forms and reinforced concrete deck for 21 bridge spans.

The next 32 girders (all Type 6) were placed in the challenging zone where the HOV bridges cross under the existing Ramp NW Bridge. The first four spans of the SB and NB bridges involve an area where the bridges are closer to the ground, space is a little tighter.


Figures 14A and 14B – Careful planning of pier locations proved invaluable for foundation drilling and girder setting. Shown are the two critical spans – at left looking south, is HOV SB Span 2 and, at right looking north, is HOV NB Span 1.

The last 16 girders (all Type 4) could not be placed until SR202L EB traffic was restored to the initial/final alignment. With the traffic detour decommissioned, the Contractor could build the last few piers and one abutment needed to complete the SB bridge.

Figure 15 – Looking south, the final abutment and four spans of the HOV SB Bridge could not be built until the detour is decommissioned and SR101L EB traffic is restored to its location under the completed portions of the HOV Bridges.

FACTS, FIGURES, AND FIRSTS

Of the 40 bridges on the SR51 Piestewa Freeway, the HOV SR51 SB and HOV SR51 NB bridges are the longest.

The HOV Bridges are the only SR51 bridges making a freeway-to-freeway system connection, and the only SR51 bridges that involve straddle bents.

The HOV Bridges are the first ADOT bridges to utilize a straddle bent system where two bridges cross over multiple straddle bents, and the straddle bent "support assignments" are divided between the two bridges.

Figure 16A and Figure 16B – Reach 11 flood control basin at onset of construction (LT); and after substructure construction is underway (RT).


Figures 16C and 16D – First framing plan mobilization involves 84 girders (LT); and as deck construction has commenced, second mobilization involves 32 girders (RT).

REFERENCE LINKS

1. Arizona DOT Regional Freeway System Map --
   http://www.azdot.gov/Highways/vpm/RegFwySysMapPM.asp

2. Arizona DOT SR51 Piestewa Freeway --
   http://www.azdot.gov/Highways/Valley_Freeways/Freeway_Maps/SR51.asp
   http://www.azdot.gov/Highways/valley_freeways/SR51/index.asp

3. Central Arizona Project --
   http://www.cap-az.com

4. City of Phoenix Parks and Recreation Department (Northeast Division) --
   ftp://www.phoenix.gov/pub/PARKS/noeas308.pdf

5. Stanley Consultants, Inc. --
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6. Stanley Consultants, Inc. Phoenix Office --
   http://www.stanleyconsultants.com/locations_us_phoenix.htm