

CHAPTER 5: CASE STUDY – THE WILSON CREEK BRIDGE

Chapter 5 comprises a constructability analysis of a real-life bridge project to enhance understanding of concepts introduced in previous chapters and give an example of how design and construction are actually carried out. This case study shall provide a link to construction engineering practice by documenting the sequence of construction phases, the techniques and resources used, and what structural and managerial considerations contributed to the project planning and execution.

5.1 PROJECT CONCEPTUALIZATION

The following sections introduce the case study project, the Wilson Creek Bridge. Apart from giving general information on the nature, location, and construction of the Wilson Creek Bridge, legal provisions set forth in the contract between owner and contractor and financial provisions will be presented.

5.1.1 General Project Overview

The bridge project to be used in this case study is located in Montgomery County in the Commonwealth of Virginia. Montgomery County is located in Salem District, which comprises twelve counties in the southwestern part of Virginia. The bridge will be crossing Wilson Creek and Ellett Road (Route 723) in Ellett Valley, which is located between Blacksburg and Christiansburg. Figure 5-1 shows the location of the project.

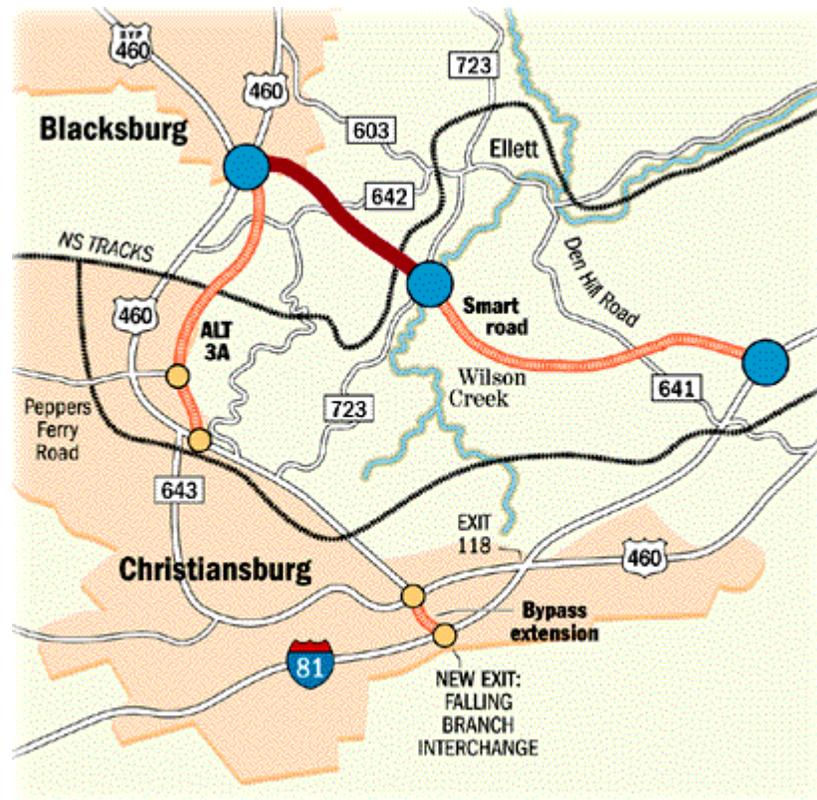


Figure 5-1: Location of the Wilson Creek Bridge (taken from The Roanoke Times 1999a)

5.1.2 Smart Road Project

The route that will run across the bridge is part of Virginia’s Smart Road project, which in turn is part of Virginia’s Smart Travel Program, as information on the Commonwealth of Virginia Department of Transportation site on the World Wide Web lines out (VDOT 1999). Following information specifically pertaining to the Smart Road was obtained from this source, unless otherwise referenced. The Smart Road project is undertaken jointly by the Commonwealth of Virginia Department of Transportation (VDOT) and the Center for Transportation Research (CTR) at Virginia Polytechnic Institute and State University. Further information from the Center for Transportation Research site on the World Wide Web (CTR 1999) also mentions involvement of the Virginia Transportation Research Council and the Federal Highway Administration (FHWA).

5.1.3 Objective of Smart Road and Overview

The Smart Travel Program is supposed to enhance quality of traveling by use of state-of-the-art technology, e.g. traveler information services pertaining to current traffic and weather conditions, and by other research projects. The Smart Road project consists of several phases with an anticipated overall date of completion of about 2015. It was initiated to do research on safer highways and vehicles (VDOT 1997a). Finally, the Smart Road will comprise a 9.2-km long highway from Blacksburg, passing Christiansburg and running to the Southeast towards Interstate I-81.

This multifunctional research facility provides an instrumented road including several pavement sections of different composition and alignment equipped with modern fiber optic communications technology, 72 snow-making towers to simulate different weather conditions, and variable lighting poles. A control and visitors center is being built to provide the necessary facilities for preparation and supervision of research being conducted and to present information on the Smart Road to the public. Construction of the aforementioned bridge with a completion date in Fall of 2000 is another important phase in the project. A smaller bridge within the project incorporates Cathodic Protection in its deck to conduct research on means of preventing corrosion of concrete bridge structures.

According to information from the Center for Transportation Research site on the World Wide Web (CTR 1999) the 2.7-km long Test Bed in the middle part of the two westbound lanes of the highway will be constructed and instrumented in stages while the eastbound lanes are prepared to grade but not paved. The Test Bed will have turnarounds at both ends to accommodate continuous driving for research purposes. A considerable amount of earthwork including a major cut through rock is necessary to construct the Test Bed.

In a later stage the westbound lanes will be connected to Blacksburg and Interstate I-81, as well as the highway parallel to the Test Bed will be constructed as a detour for the through traffic. Research can continue on the Test Bed after the highway has been opened for through traffic with one lane in each direction. Finally, construction of the remaining parts of the eastbound lanes will provide a two-lane divided highway. For these eastbound lanes a bridge similar to the

Wilson Creek Bridge would be built (VDOT 1997b). Figure 5-2 schematically shows the Smart Road project.

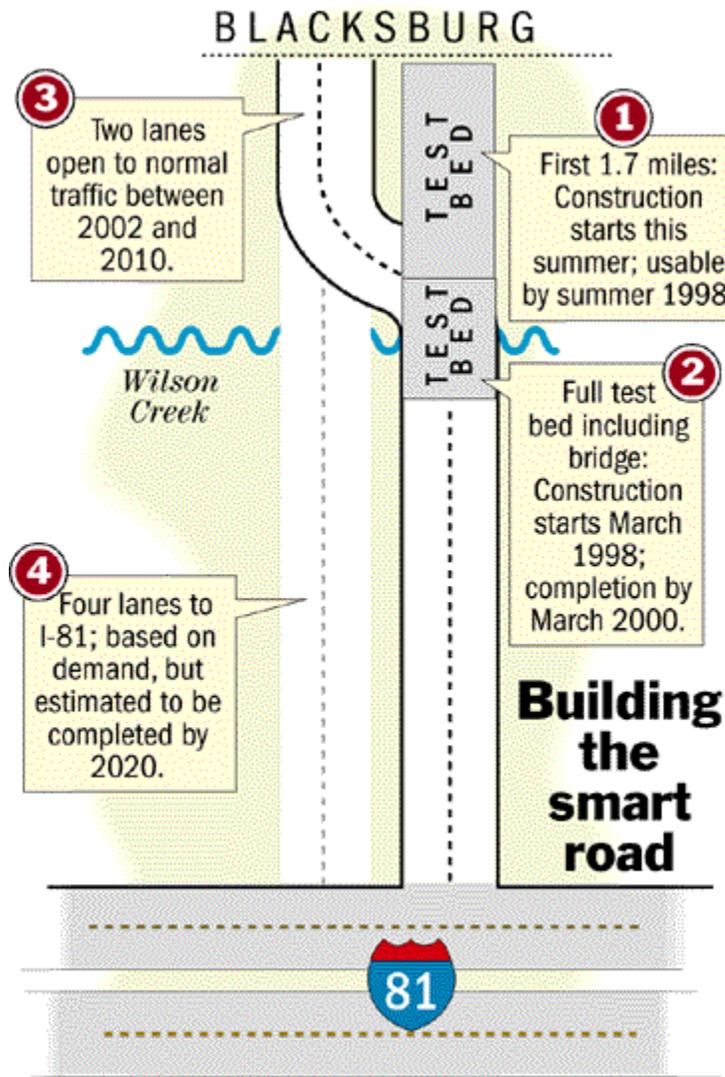


Figure 5-2: The Smart Road Project (taken from The Roanoke Times 1999b)

5.1.4 Regional Traffic Infrastructure

Apart from the outlined research determination the second major function of the Smart Road is to provide a new two-lane divided highway. It will finally serve the growing traffic volume as a

better connection than the current Route 460 between the Town of Blacksburg and Interstate I-81, which runs through Southwest Virginia following the direction of the scenic Blue Ridge Mountains. Thus, both research interests and improvement of regional traffic infrastructure are accommodated in this project. Positive effects on the regional economic development are anticipated.

5.1.5 Bridge Overview

The bridge to be built is a cast-in-place concrete segmental bridge. Because of being part of the Smart Road project, the bridge is also colloquially referred to as the Smart Highway Bridge, or simply the Smart Bridge. It will cross Ellett Valley with five spans that add to a total length of 605.00 m. Three central spans have a length of 144.00 m each, the side spans are 86.50 m wide (VDOT 1997c), measured center-to-center. The bridge superstructure consists of a single box girder with cantilevering flanges. It has a varying depth that reaches its maximum at the piers.

The Wilson Creek Bridge is built utilizing Balanced Cantilever Construction, which has been introduced in Section 4.2.1.3. This special erection method for a major segmental bridge is still somewhat rare in the U.S. Cantilevering will subsequently be performed about each of the four piers until midspan is reached with the respective cantilever arms. Piers are hollow cast-in-place shafts with a vertical taper. They are numbered 1 through 4 between Abutment A on the northwestern end of the bridge and Abutment B on the southeastern end of the bridge.

The alignment of the bridge is straight without any horizontal curvature. There is, however, “a constant 6% vertical down grade”, which leads “into a 700 meter vertical sag curve just past the center of span 3” (Janssen & Spaans 1999a, p1). In the transverse direction the slope of the bridge deck is constant with 2 % for drainage of the bridge deck. Figure 5-3 shows the overall elevation of the bridge.

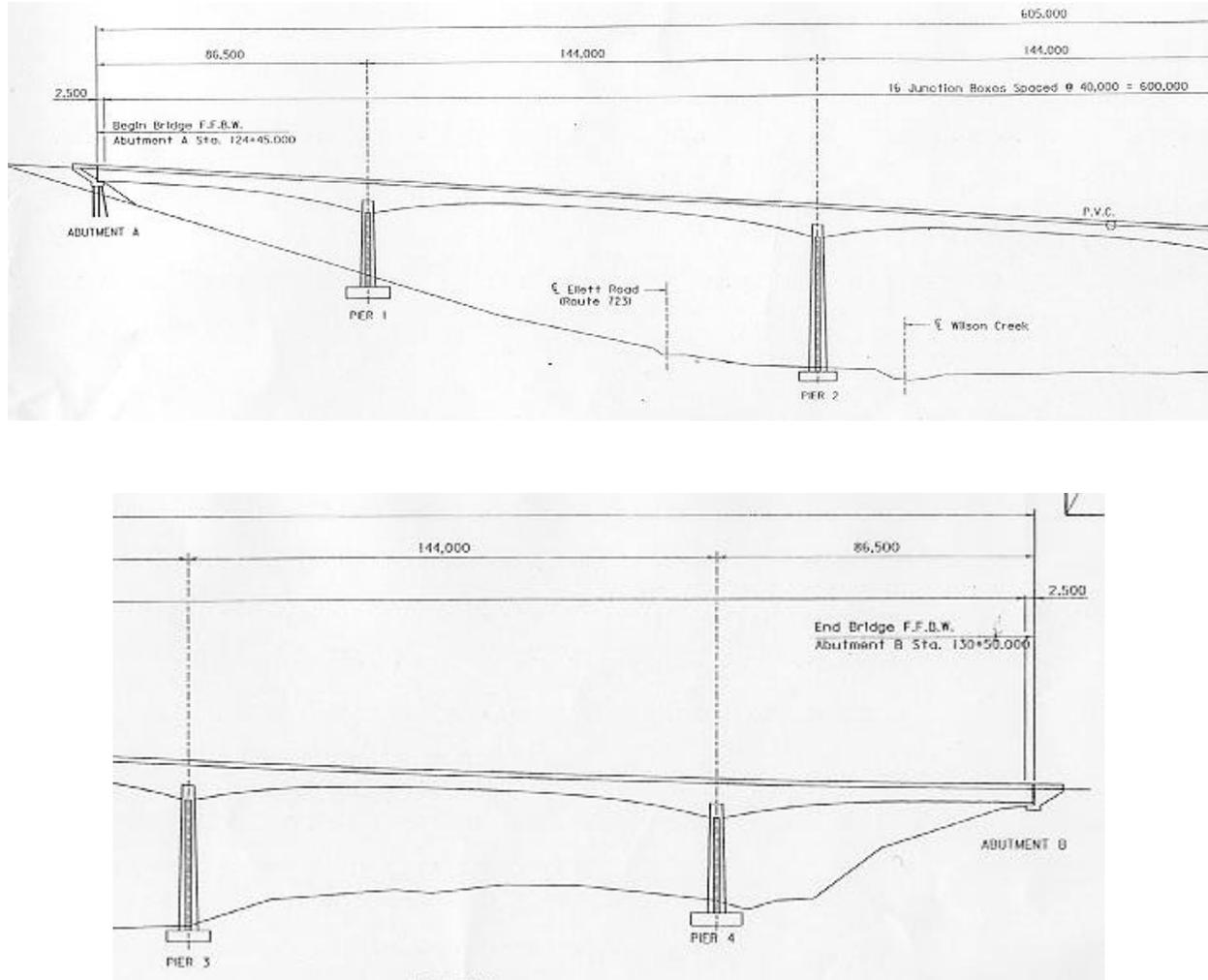


Figure 5-3: Overall Elevation of the Wilson Creek Bridge (taken from VDOT 1997c, p1)

5.1.6 Parties Involved

Owner of this bridge structure is the Commonwealth of Virginia Department of Transportation (VDOT). VDOT, represented through its Structure and Bridge Division assigned the task of bridge design for bidding purposes to Figg Engineers, Inc. of Tallahassee, FL. The shop drawings for actual project execution were prepared by Janssen & Spaans Engineering, Inc. of Indianapolis, IN, consulting engineers to the contractor, PCL Civil Constructors, Inc. of Coral Springs, FL (PCL).

Other parties involved in construction of the project were the subcontractors and suppliers. Of particular interest in this study is the company that manufactured the form travelers for the Wilson Creek Bridge, AVAR Construction Systems, Inc. of Campbell, CA. More information on the functioning of these pieces of equipment is provided in Section 5.3.4. Figure 5-4 shows the major contractual parties involved in the Wilson Creek Bridge project.

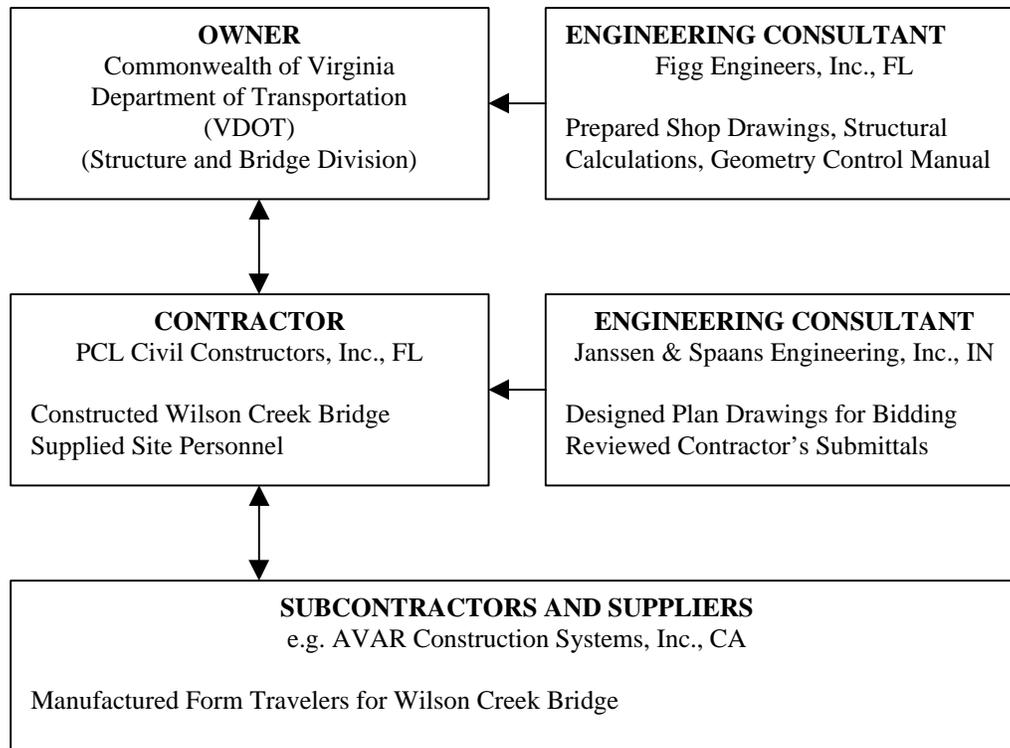


Figure 5-4: Contractual Parties

5.1.7 Contractual Provisions

Comprehensive bidding documents were set up by the owner for the bridge project to be examined in this study. Submittal of the documents completed by bidders was on February 24, 1998. An interesting prequalification requirement for bidders was submittal of proof of three

previously completed concrete segmental bridges including a narrative of related experience and resumes for each “of the bidder’s individual Project Team members” (VDOT 1998, p35).

Low bidder for this project was PCL Civil Constructors, Inc. of Coral Springs, FL. Total bid value for the project was \$ 14,647,120.00. On June 1, 1998 this low bid was accepted and recommended to the Commonwealth Transportation Board of Virginia, which awarded the contract to PCL (VDOT 1998).

The contract bears the contract identification number C00016931C02, the project number given in these documents is (FO) IVHS-060-0101, C502, B603. The abbreviation IVHS stands for Intelligent Vehicle-Highway System. Overall, this specific part of the Smart Road project comprises construction of 0.860 km of grade, drain, traffic control devices, asphalt pavement, and the bridge itself within the framework of the aforementioned Smart Road project. The fixed end date specified for the whole Design-Bid-Build project is June 1, 2000 (VDOT 1998).

In the contract and on the plans it is stated that construction of the Wilson Creek Bridge and the surrounding works needs to adhere to the following legal provisions (VDOT 1998):

- VDOT Metric Road and Bridge Specifications (January 1997);
- VDOT Road and Bridge Standards (January 1994);
- Virginia Work Area Protection Manual (January 1996);
- Special Provisions and Special Provision Copied Notes (as listed in the contract).

Thus, the General Provisions and the Specifications set forth in the aforementioned documents effectively become part of the contract. In come cases they are modified by the Special Provisions that are written specifically for this project. For this reason, special provisions are also called Project Provisions.

Most of the contract document for the Wilson Creek Bridge thus consists of alterations of parts of sections from the aforementioned generic legal provisions. Alterations of the General

Provisions adjust the contractual relationship between the Contractor PCL and the Owner VDOT to the specific needs of the project. Alteration of Specification that are provided by the contract deal with a broad variety of construction materials and supplies, and testing thereof, as well as with specific construction techniques, control thereof, and requirements to protect the natural environment. Information on gas, electricity, and communications lines is also given. Finally, the contract contains e.g. Federal-Aid Construction Provisions pertaining e.g. to payments and Equal Employment Opportunity (EEO) and Disadvantaged Business Enterprises (DBE) requirements (VDOT 1998).

5.1.8 Financial Provisions

A large variety of separate payment items are mentioned in the contract documents for the Wilson Creek Bridge. A revised schedule of liquidated damages is provided in the contract that determines the daily charge of liquidated damages for different original contract values; for the Wilson Creek Bridge with a contract value between \$ 8,000,000 and \$ 15,000,000, a sum of \$ 1,100 of liquidated damages per day is determined. The contract documents determine with respect to payments (VDOT 1998, p69):

“Partial payments will be made once each month for the work performed in accordance with the contract requirements... (...) When the value of the value of the work completed on critical operations detailed on the earnings schedule is behind the value of the work planned for these operations by more than 10 percent, the Contractor may be notified that if the next monthly progress estimate shows a delinquency of more than 10 percent, progress will be considered unsatisfactory and 5 percent retainage will be withheld for each month the Contractor is behind by more than 10 percent.”

The following compilation gives a brief overview of how individual items are paid for (VDOT 1998):

- Lump Sum Items:

Site mobilization works (paid for in two parts), construction surveying, concrete surface color coating, work bridge across Wilson Creek, equipment for segmental erection (50 % retainage until completion of first segments).

- Unit Price Items:
Material for storm water management (SWM) system, pavement, deck drainage, piles, tooth expansion joints, conduits, guardrails, aggregate material, miscellaneous minor items, backfill material.

- Monthly Rate Items:
Field office.

Many details are incidental costs to the member in which they are installed. The main construction materials, i.e. concrete, mild reinforcement, and post-tensioning steel will be paid for as follows (VDOT 1998):

- Concrete and mild reinforcement is both paid for by unit price “complete-in-place” (VDOT 1998, p139); with concrete being paid for per cubic meter and epoxy-coated reinforcement being paid for per kilogram. Labor cost and details related to the concrete structure, such as blockouts or formwork are incidental to this cost.

- Post-tensioning steel tendons are all paid for per kilogram, including equipment and labor cost for installation operations of the tendons. Ducts and anchorages are incidental cost to the cost for the tendons themselves.

- Mass concrete, as found in the pier tables is a separate payment item, which is paid for by cubic meter.

- Latex-modified concrete for the bridge deck is paid for per cubic meter, its placement is paid for per square meter.

5.2 PROJECT DESIGN

The following sections give a more detailed description of the structural system of the bridge and information that plans and specifications provide for the bridge project. The main elements of the bridge, namely foundations, substructure, superstructure, and supplementary works will be briefly described and their characteristics will be lined out. Special consideration is given to documents that provide a detailed outline of the steps of the erection sequence and of control mechanisms.

5.2.1 Member Designation

Cantilevering the box girder spans will begin on both sides of the pier tables in the so-called Up Station and Down Station directions. *Up Station* denotes the direction from the pier table towards Abutment B; the so-called B-segments that are on the Up Station side of every pier thus carry a *U* in their identification number. *Down Station* denotes the direction from the pier table towards Abutment A; the so-called A-segments that are on the Down Station side of every pier thus carry a *D* in their identification number. This notation is not consistent with the overall longitudinal slope of the bridge and may therefore initially be confusing.

However, the technical explanation for this denotation arises from overall site surveying. As the project ‘start’ is located at the northeast end, all counting and naming begins at that location. Station marks begin with zero at Abutment A, thus determining the Up Station direction towards the other abutment. Abutment A is followed by Piers 1 through 4 and Abutment B. Spans are numbered 1 through 5 in the Up Station direction. An example of the segment designation is shown in Figure 5-5.

All superstructure segments have a unique identifying code that comprises the pier number, the Up Station or Down Station direction for that particular pier, and the number of the segment in the respective half span. A segment designation thus could e.g. be P1-U7, i.e. segment number 7 in the cantilever arm in Up Station direction from Pier 1. Shop drawing sheets are numbered according to this segment designation.

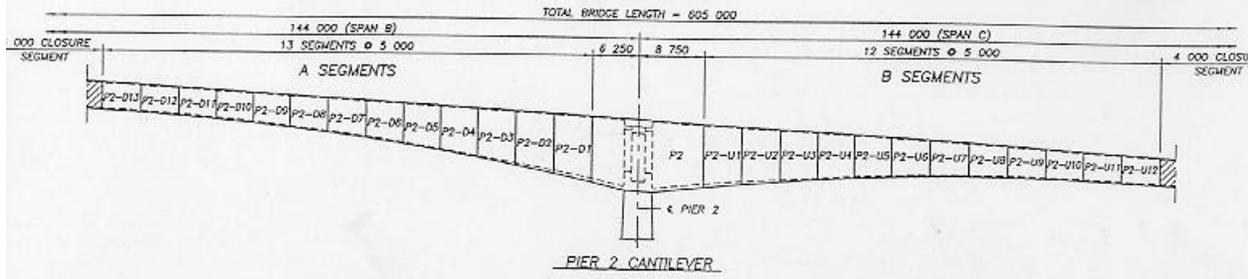


Figure 5-5: Segment Designation for Cantilever Arms About Pier 2
 (taken from Janssen & Spaans Engineering, Inc. 1998, pS1)

Further special notation is provided for joints between individual segments. Segment joints in the Down Station cantilever arms are denoted alphabetically by two letters, segment joints in the Up Station cantilever are denoted alphabetically by one letter only. Tendons are denoted with a two-part code. The first part, *B* or *T* and a number tells that the tendon is a bottom slab continuity tendon or a top slab cantilever tendon in a particular span, the second part is a number giving the correct order of post-tensioning.

5.2.2 Member Geometry

After having familiarized with the designation of structural members, in particular superstructure segments, an overview of their dimensions will be given in the following.

5.2.2.1 Foundations

Both abutments rest on footings that are 4.05 m long, 12.00 m wide, and on average 1.30 m deep. The embankment under Abutment A, which is constructed on a fill, consists of grouted riprap to stabilize the slope of 1 to 1.5 (VDOT 1997c). This abutment will be founded on a grid of piles, as the fill itself cannot provide sufficient load-carrying capacity. For Abutment B a simple spread

footing is sufficient for the necessary load-carrying capacity, as well as for all pier footings. Pier footings are massive concrete plates of 14.00 m square and 3.50 m thickness for piers 1 and 4, and of 12.00 m square and 3.00 m thickness for Piers 2 and 3 (VDOT 1997c).

5.2.2.2 Abutments

Abutments A and B are both normal wing wall abutments and identical in size, except for the difference in their foundations, as mentioned in the previous paragraph. Overall abutment dimensions are 12.00 m width and 10.00 m length. The lower wing wall edge has a slope of 67.45 to 100 in Abutment A or 60 to 100 in Abutment B, respectively. Abutment wing walls extend from the breast walls backward in a 90° angle. Abutment A furthermore incorporates the overall 6 % longitudinal slope of the bridge alignment (VDOT 1997c).

Bearings for the bridge superstructure will sit on special blocks called concrete riser pads, which are cast onto the bridge seat. Abutment interiors are accessible for inspection of bearings and maintenance works. Furthermore, according to the plan drawings drainage aggregate and piping is to be installed behind the abutment.

5.2.2.3 Pier Shafts

All piers are rectangular hollow cast-in-place boxes with a vertical taper on all sides. The following Table 5-1 gives an overview of the four piers and their main dimensions, with depth measure in the longitudinal direction of the bridge superstructure and width in the transverse direction (VDOT 1997c, pp20f). The Wilson Creek Bridge will be the tallest bridge in the Commonwealth of Virginia.

The piers are tapered on all sides. This taper is constant 1 to 40 on the faces in the longitudinal axis of the bridge, and 1 to 50 on the faces in the transverse direction. Pier shaft walls are 0.40 m thick facing the longitudinal axis and 0.80 in the transverse direction (excluding the depth for the natural stone inlays). The rectangular shape of the piers is carried higher to about half the height

of the box girder that are tapered in the opposite direction, as the box girder has the least width at its bottom. Detailed plan drawings show this intersection of pier shaft and box girder webs. The part of the superstructure that is located directly above the pier shaft is called pier table. A view of Pier 2 is provided in Figure 5-6. The taper and the vertical niches for the natural stone inlays are clearly visible.

Table 5-1: Pier Dimensions of Wilson Creek Bridge

Dimensions	Pier 1	Pier 2	Pier 3	Pier 4
Height from footing top to girder bottom	24.524 m	41.314 m	38.514 m	25.943 m
Top width	6.000 m	6.000 m	6.000 m	6.000 m
Top depth	3.750 m	3.750 m	3.750 m	3.750 m
Bottom width	6.982 m	7.654 m	7.542 m	7.040 m
Bottom depth	4.978 m	5.818 m	5.678 m	5.050 m



Figure 5-6: Pier 2 Prior to Construction of Pier Table

As mentioned in Section 3.3.5, the bridge piers are architecturally shaped and decorated with natural stone inlays. Figure 5-7 shows the planned elevation of the top of a bridge pier. The asymmetry of the pier table is clearly visible. Vertical niches for natural stone inlays have a constant width of 2.50 m on the pier shaft faces perpendicular to the longitudinal bridge axis and of 1.50 m width perpendicular to the transverse direction. These inlays end at the lower edge of the superstructure box girder. For sufficient support of the stone inlay, steel angles and dovetail anchors that sit in anchor slots cast into the concrete surface are planned.

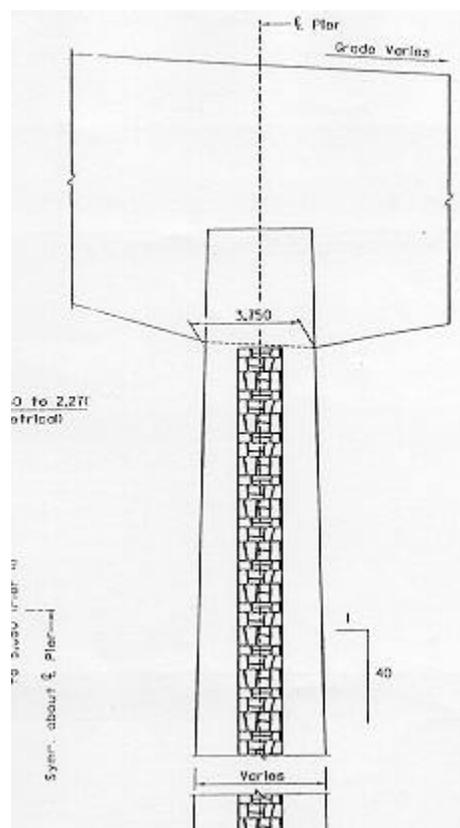


Figure 5-7: Architectural Shaping of Pier Shaft and Pier Table
(taken from VDOT 1997c, p229)

5.2.2.4 Pier Tables

Pier tables are major elements within the structure. As the box girders reach their maximum depth at this point and form a rigid connection between superstructure spans and the piers below, the pier tables are considerably large and massive elements. Several single concrete placements are necessary to construct them. Separate plan drawings provide all dimensions of the pier tables. They have a depth of 9.50 m; two 1.00-m thick vertical diaphragm walls within the box girder of the pier tables with a narrow vertical access opening in the middle facilitate transfer of the flow of forces from the superstructure into the bridge piers (VDOT 1997c). In the area of the pier tables the box girder webs have additional reinforcement (Janssen & Spaans Engineering, Inc. 1998).

Pier tables are not exactly symmetrical in the Up Station and Down Station direction as seen in Figure 5-7, but are built with a difference between both sides of half a segment length. This imposes a certain imbalance in construction of the superstructure. Other causes for imbalances have been described in Section 4.3.2.

5.2.2.5 Superstructure

The cross-section of the superstructure is a single-cell box girder, consisting of the top slab with cantilevering flanges, webs, and the bottom slab. The box girder webs have a constant vertical inclination of 10.61 to 100. Connections between webs and top slab are haunched. At the outside edge under the cantilevering flanges these haunches are not straight but rounded with a radius of 0.60 m. Thickness of the cantilevering flanges is constant with 0.23 m at the edges. Web thickness is constant with 0.40 m over the whole length of the superstructure.

Overall width of the top slab is 12.00 m, including the cantilevering flanges of about 2.10 m width each. The box girder will carry two lanes of traffic that are each 3.60 m wide. The bridge deck has a transverse slope of 2% for drainage purposes and will carry a Kansas Corral type railing at its edges.

Plans initially foresaw a pier table segment of 6.00 m length with about half a segment length asymmetry to the pier shaft centerline. Superstructure segments of type I, which are close to the pier table were planned to be 2.25 m long. All other superstructure segments are called type II and were planned to be 4.50 m long, with 3.00-m long closure segments at midspan. Type III segments, being the last few segments directly at the abutments, were planned to have constant depth. They will be constructed separately on falsework. Originally the end sections with type III segments were planned to be 12.55 m long at Abutment A and 14.80 m long at Abutment B. The different originally planned segment types for the example of the cantilever arms about Pier 2 are shown in Figure 5-9.

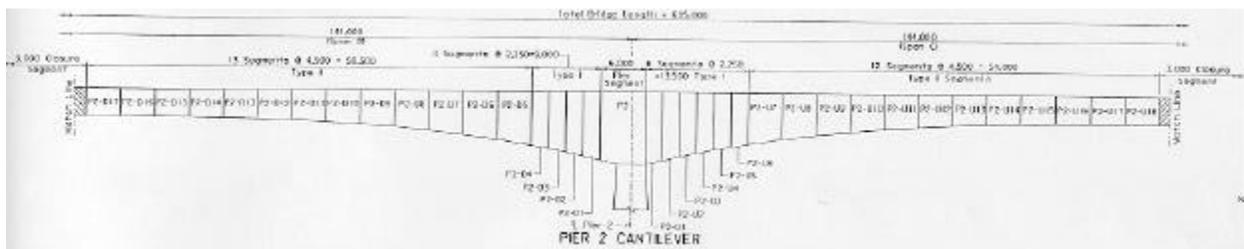


Figure 5-9: Originally Planned Segment Dimensions (taken from VDOT 1997c, p27)

The difference in segment length with decreasing segment depth towards midspan supposedly was planned to level volumes of concrete placements during construction. Bottom slab thickness was planned to be reduced over the type I segments gradually to 0.25 m in thickness and was planned to remain constant for all type II segments in the span.

Diaphragms of 1.875 m thickness are situated over the bridge bearings in the last box girder segment directly adjacent to the abutments. It is heavily reinforced around the approximately triangular access opening because of the several prestressing tendons ending at it (VDOT 1997c).

5.2.2.6 Surrounding and Incidental Works

A variety of works not directly related to the bridge structure are to be performed under the contract. Detailed information on these works is found in the first part of the plan drawings (VDOT 1997b), with the second part being plan drawings exclusively dealing with the Wilson Creek Bridge itself (VDOT 1997c). Most importantly, a drainage system is to be constructed on the eastern side of Ellett Valley, consisting of a concrete box culvert and a basin adjacent to Wilson Creek. The storm water management (SWM) basin has a cast-in-place concrete dam of about 2.00 m height and about 12.00 m width (VDOT 1997b). Standard and custom details for drainage items of the Wilson Creek Bridge project, e.g. an energy dissipator, concrete pipes, junction boxes for the box culvert, and the like are provided in the plans. The box culvert provides a canal that is accessible through manholes, running downhill including two forks in a part of the valley on the northeastern side of the construction site. It was designed for the maximum expected flow of water.

Erosion and siltation control on site required installation of perimeter barriers. Furthermore, rock check dams were to be built along the drainage structure to prevent increased erosion of the slopes of the valley during excavation works (VDOT 1997b). Re-landscaping of the cut and fill areas will be carried out according to the seeding plan prepared by VDOT (1997b).

5.2.3 Change in Design

The contract documents for the Wilson Creek Bridge provide the following for Value Engineering Proposals by the contractor regarding the superstructure segmentation (VDOT 1998, p36):

“The Contractor may propose modifying the length of the Pier Table and/or individual superstructure segments to facilitate his means and methods considering the form traveler system that he selects. Modifying the segment lengths will likely necessitate a change to the cantilever post-tensioning. Any modification to the cantilever post-tensioning system will be accomplished without modifying the concrete section dimensions. The Contractor shall request approval for any modification sufficiently early as to allow review, comments,

revisions/re-submittal and subsequent acceptance (or rejection) without affecting the Contractor's schedule.

The contractor demonstrates that any proposed option or modification meets all aspects of the design criteria.”

As mentioned, plans originally foresaw a segment length of 4.50 m with 3.00-m long closure segments. Pier tables were designed to be 6.00 m long; with four or six type I segments of 2.25 m length directly adjacent to the pier table. The number of type II segments in the cantilever arms was planned to be 13 or 12, respectively. Overall, segments lengths in the center spans would sum up to 144.00 m.

PCL Civil Constructors, Inc., the contractor, made the proposal to change the length of the 13 or 12 segments, respectively, to 5.00 m and have a 4.00-m long closure segment. The pier table should have a length of 15.00 m, with an asymmetry of 2.50 m, half a segment length. The overall span length would remain unchanged with 144.00 m. Also, the end sections with type III segments were changed in length to 15.05 m at Abutment A and to 17.55 m at Abutment B. The redesigned length of the segments is at the upper end of what is technically common. Shop drawings and calculations for this major design change were produced by Janssen & Spaans Engineering, Inc. and approved by the owner (Janssen & Spaans Engineering, Inc. 1998). Figure 5-10 shows the new segment dimensions in the cantilever arms about Pier 2; other spans are similar in arrangement.

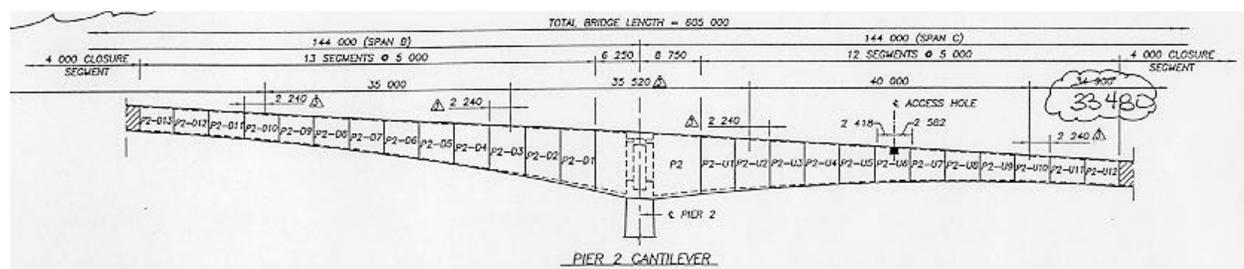


Figure 5-10: Changed Segment Dimensions
(taken from Janssen & Spaans Engineering, Inc. 1998, pS14)

On the Down Station side of the asymmetric pier table, 13 segments of 5.00 m length are placed in the cantilever arm, on the Up Station side there will only be 12 segments, as pier tables are longer by half a segment length in this direction. The so-called leading direction, meaning where the actual Balanced Cantilever Construction started was Up Station; segment number 1 on the Down Station side of the pier table is not counted as an actual cantilevered segment. Hence, 12 cycles for segments of the same type have to be completed in each cantilever arm.

This change in segment length required redesign of the form traveler specifications and the data for segment geometry and results and larger volumes of concrete to be placed per individual segment. Revised segment dimensions, e.g. the thickness of the box girder bottom slabs at each joint are provided in separate tables in the shop drawings (Janssen & Spaans Engineering, Inc. 1998). Bottom slab thickness decreases from 1.25 m in the pier table to 0.5 m, 0.4 m, 0.3 m, and then remains constant with 0.25 m in all further segments in the cantilevering span. However, the major advantage of working with longer segments of one type only and a longer pier table element is that the Balanced Cantilever Construction is simplified and that the number of casting cycles is effectively reduced over the whole span.

5.2.4 Quantities of Construction Materials

The following Table 5-2 gives an overview of the quantities of construction materials in the different parts of Wilson Creek Bridge (VDOT 1997c, p4), excluding surrounding works, such as excavation for drainage box culverts, etc.

Table 5-2: Quantities of Construction Materials for Wilson Creek Bridge

Part	Quantities
Superstructure	6,451 m ³ class 55 concrete 710,030 kg epoxy-coated reinforcing steel 308,610 kg longitudinal post-tensioning steel 44,960 kg transverse post-tensioning steel 6,897 m ² latex-modified concrete overlay 22,154 m ² surface coating 24 m tooth expansion joint 1,210 m cast-in-place Kansas Corral type railing
Abutments A, B	(Each): 2 pot bearings (Each): 63 m ³ class 30 concrete footing, 81 m ³ class 30 concrete neat (A): footing 6,686 kg coated steel, neat 8,190 kg coated steel (B): footing 6,686 kg coated steel, neat 8,100 kg coated steel (A): 200 m steel piles (310 mm)
Pier 1	686 m ³ class 30 concrete footing, 325 m ³ class 55 concrete neat 50,070 kg uncoated steel footing, 140,900 kg uncoated steel neat
Pier 2	432 m ³ class 30 concrete footing, 492 m ³ class 55 concrete neat 23,510 kg uncoated steel footing, 119,390 kg uncoated steel neat
Pier 3	432 m ³ class 30 concrete footing, 452 m ³ class 55 concrete neat 23,510 kg uncoated steel footing, 112,860 kg uncoated steel neat
Pier 4	686 m ³ class 30 concrete footing, 346 m ³ class 55 concrete neat 50,070 kg uncoated steel footing, 146,850 kg uncoated steel neat
Total	8,066 m ³ class 55 concrete 2,524 m ³ class 30 concrete 667,160 kg uncoated reinforcing steel 739,692 kg epoxy-coated reinforcing steel 353,570 kg post-tensioning steel 10,014 m ³ structure excavation

With respect to material properties, the largest amount of the concrete for superstructure and substructure will have a minimum specified 28-day strength f'_c of 55 MPa. Concrete for the Wilson Creek Bridge is low permeability concrete. According to the Project Engineer the concrete used in the Wilson Creek Bridge has considerable high early strength. The minimum required compressive strength of 30 MPa for stressing segments is actually reached in less than 24 hours after placement on site, as determined from samples taken during construction (PCL 1999d).

The yield strength of the ASTM A615M mild reinforcement f_y is 420 MPa. Post-tensioning tendons are of type ASTM A416, grade 270, with low relaxation and have an ultimate strength f_{pu} of 1,862 MPa. Post-tensioning tendons in the Wilson Creek Bridge are composed of 19 individual strands that consist of seven 15.24-mm thick wires each (VDOT 1998).

5.2.5 Reinforcement and Related Details

This section shall introduce to the arrangement of mild and prestressing steel in the Wilson Creek Bridge. The special focus lies on the layout of the post-tensioning tendons.

5.2.5.1 Concrete Cover

For the Wilson Creek Bridge the following values for minimum concrete cover of reinforcement are specified to provide adequate protection of the reinforcement against detrimental environmental influences that might cause corrosion (VDOT 1997c, p5):

<i>a. Superstructure</i>	
<i>All external and internal surfaces except top slab</i>	<i>40mm.</i>
<i>Riding surface where protected by overlay</i>	<i>50mm.</i>
<i>Bottom of top slab between webs</i>	<i>25mm.</i>
<i>b. Substructure</i>	
<i>Abutment walls</i>	<i>70mm</i>
<i>Ties and spirals</i>	<i>60mm</i>
<i>Internal side of hollow pier</i>	<i>50mm”</i>

5.2.5.2 Prestressing Tendons, Tendon Ducts, and Anchorages

Arrangements of post-tensioning tendons and their sequence of post-tensioning and stressing forces are provided in the plans (VDOT 1997c) and in more detail in the shop drawings (Janssen & Spaans Engineering, Inc. 1998). Schemes of the prestressing tendons in plan view and elevation show the tendon profile and determine stressing and non-stressing ends of the tendons.

These profiles are similar for all spans of the Wilson Creek Bridge. Exceptions are the end spans near the bridge abutments. In those locations, the bottom continuity tendons run towards the upper slab.

Tendons are anchored surrounded by spiral reinforcement in anchorage blocks, also called blisters, which are located on the inside bottom slab edges of the box girder in a symmetrical fashion. Blister weight is to be included in calculations and quantity take-offs. They are reinforced and furthermore contain spiral reinforcement to better distribute compressive forces induced in the concrete by the post-tensioning force. Some of the blisters within the hollow box girder incorporate empty ducts that are provided for inserting additional external post-tensioning tendons that might become necessary some time in the future because of increased traffic loads. However, according to the shop drawings no spiral reinforcement is provided for these empty tendon ducts.

Tendon anchorages for transverse prestressing tendons are located in blockouts in the edge of the cantilevering flanges that will be filled with non-shrink concrete after post-tensioning. The arrangement of transverse tendons in the pier table diaphragm is shown in Figure 5-11.

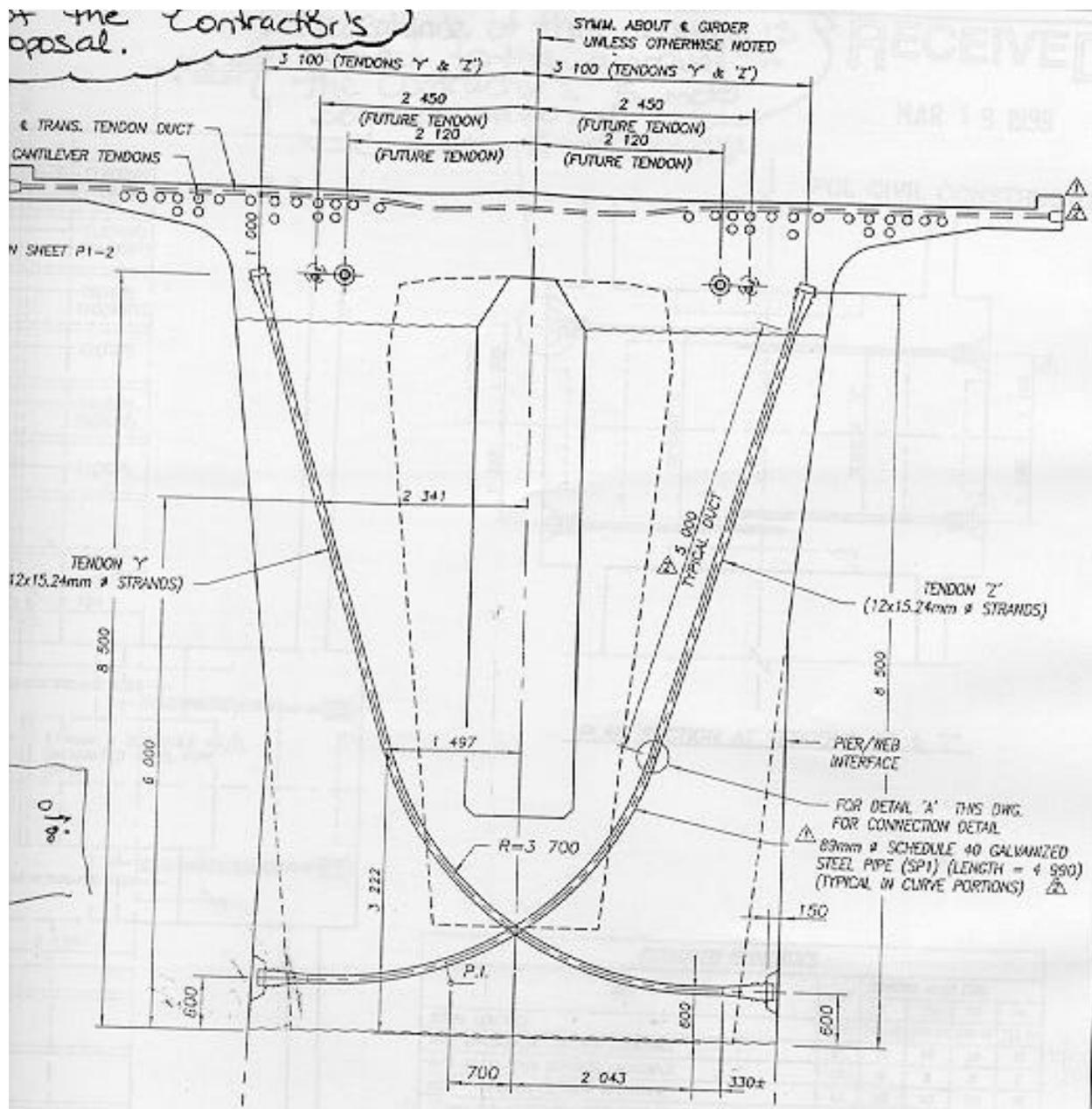


Figure 5-11: Arrangement of Transverse Tendons in Pier Table Diaphragm
(taken from Janssen & Spaans Engineering, Inc. 1998, p1-3)

Tendon ducts have to be galvanized corrugated steel ducts for all longitudinal tendons and corrugated polyethylene or steel flat ducts for transverse tendons (VDOT 1997c). The tendon

ducts will be coupled with special duct couplers. So-called grout vent tubes are incorporated in the tendon ducts to ensure that the ducts will be completely filled with grout after prestressing.

Tendons have a bent at their end that leads them from the slab in which they are located into the anchorage block. Certain bending radii must be adhered to in arrangement of the tendons to prevent spalling of the corrosion protection layers around them. Sheet S19 and other sheets of the shop drawings show how some bars of the transverse mild reinforcement in the bottom slab may be field bent to accommodate the cable ducts.

Longitudinal cantilever tendons are located in the joint areas of top slab and webs. Naturally, they will be stressed beginning with the shortest tendons that connect only a few segments. With growing cantilever more segments need to be connected by inserting and stressing of longitudinal tendons. Stressing of the tendons will be performed on newly cast segments prior to stripping of the forms in an alternating manner on the end at which the newly cast segment is located (PCL 1999d). This sequence is expected to generate a more even distribution of prestressing forces, including losses of prestress, in the superstructure. An example of the arrangement of the longitudinal cantilever tendons in the top slab is shown in Figure 5-12.

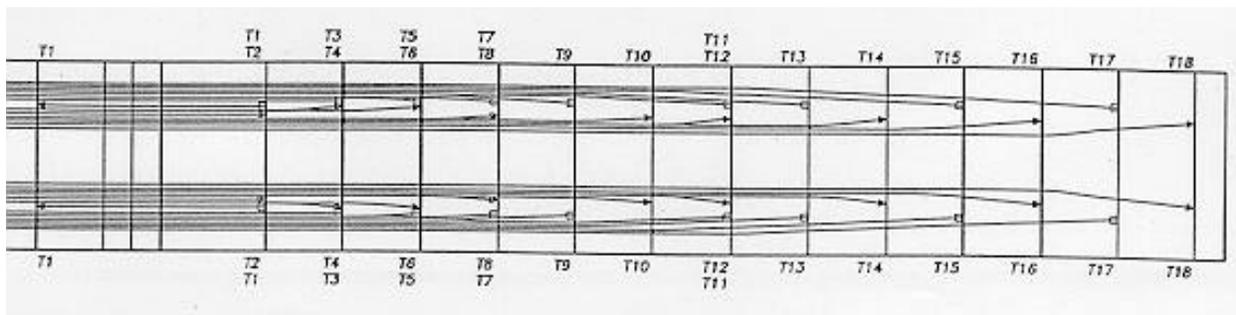


Figure 5-12: Arrangement of Longitudinal Cantilever Tendons
(taken from Janssen & Spaans Engineering, Inc. 1998, pS4)

The shortest continuity tendons that are located at midspan at the outside edges of the bottom slab are to be stressed first. Afterwards the longer tendons on the inside of the bottom slab reaching further towards the piers are stressed.

Several pairs of triplets of prestressing bars are used for vertical prestressing of the abutment diaphragms instead of tendons. Vertical prestressing tendons are also found in the pairs of diaphragms within all pier tables of the Wilson Creek Bridge. These tendons are running in a curve from the top slab through the sides of the pier tables diaphragm to the outside bottom slab edge on the other side of the bridge, thus intersecting in the lower half of the diaphragms.

5.2.5.3 Segment Reinforcing Schedule

The Segment Reinforcing Schedule provides tables that list all reinforcement for a particular segment, include the reinforcement tagging code, length, location, amount, and weight. The reinforcement denotations consist of two letters and four digits. The Segment Reinforcing Schedule provides updated information from the original Reinforcing Steel Schedules that were supplied in the plan drawings. Shop drawings provided by the contractor's consulting engineers show the reinforcement with dimensions and bending shapes. Segments in corresponding locations in the spans at different piers can have similar reinforcing, which is then noted on the particular Segment Reinforcing Schedule.

5.2.6 Further Construction Details

Three major groups of construction details are identified for the Wilson Creek Bridge. These are the bearings with which the superstructure rests on the abutments at its very ends, the expansion joints that are also located at that place, and finally accessory details and finishing works.

5.2.6.1 Bearings

The superstructure of Wilson Creek Bridge will rest on a pair of bearings at each abutment; connections between the intermediate piers and the superstructure are rigid. The plans give information on the design loads for the bridge bearings. Each bearing will have to carry between 1,850 kN and 4,000 kN vertically and 225 kN horizontally. In addition to this, the bearings must be able to provide 200 mm of horizontal longitudinal movement in both directions, adding up to a total of 400 mm, and 0.03 radians of rotation capacity. Bearing types specified in the plan drawings are guided pot expansion bearings, although differing types of bearings may be used subject to approval of the owner (VDOT 1997c). Bridge bearings are very sensitive parts of the structural system and are susceptible to increased wear and tear. Therefore, provisions for replacement of single bearings by means of lifting the superstructure with hydraulic jacks are also found in the plans (VDOT 1997c). Hydraulic jacks and bearing plates will be placed next to the original bearings to lift off the box girder by a maximum of 25 mm for replacement of old bearings.

5.2.6.2 Expansion Joints

Expansion joints are located at both ends of the superstructure to provide a connection between bridge deck and abutments. The expansion joints are tooth-type elements (VDOT 1997c). Proper positioning of the prefabricated elements that are set into the joint gap is important to allow unrestricted superstructure movements as specified and to guarantee riding comfort for future traffic. Expansion joint replacement procedures are outlined in the plan drawings (VDOT 1997c).

5.2.6.3 Accessory Details and Finishing

Plans drawings (VDOT 1997c) for the Wilson Creek Bridge give information on the various details for installations to be built into the bridge superstructure. The interior of the superstructure box girder will be accessible and requires metal stairs and walkways with railings

to pass through the pier tables. Responsibility for final detailing of these items is assigned to the contractor. Access doors and concrete stairs within the hollow abutment are planned to allow inspection of the bearings and access to the interior of the box girder, since the bridge piers themselves will not contain stairwells for access.

Drainage junction boxes with drainage conduits will be installed at the outside edges of the bridge deck at a maximum spacing of 40 m. Moreover, several multi-ducts and conduits will run along the inside of the box girder. Threaded inserts and channel inserts are to be cast into the inside surface to attach the conduits to them. In abutments and pier shafts, several weep holes are planned to allow drainage of condensation water and prevent corrosion.

Finally, the bridge itself requires finishing works and installations. Approach slabs will be built at both ends of the bridge. The railing on both sides of the bridge deck will be of the so-called Kansas Corral type, made from cast-in-place concrete. Guardrails need to be installed. The detailing of the railings with barrier delineators and curbs is also the contractor's responsibility, as the plans merely provide a copy of the standard detail. The terminal wall of the railing will be decorated with a natural stone inlay in a manner similar to the bridge piers.

A latex-modified concrete pavement overlay needs to be constructed and pavement marking needs to be applied. The concrete surface will be sealed. Drip and edge beads will be cast into the cantilevering flanges of the top slab. Minor cracks and spalling that may have occurred during construction will be repaired before final approval.

Other work items are installations necessary through the traffic control device plan. Lighting of the new highway and provision of overhead signs is necessary. Finally, cylindrical special design bunkers with access manholes and conduits for the Smart Road instrumentation and data recording devices need to be built as part of the contractual works (VDOT 1997b).

5.2.7 Plan Documents, Structural Calculations, and Construction Manuals

In the following paragraphs a brief description of the documents related to construction of the Wilson Creek Bridge are given, excluding the already mentioned contract documents.

5.2.7.1 Plans

All plan measurements and specifications are provided in the Metric System, however, the contract documents state the following (VDOT 1998, p25):

“The Department [VDOT] recognizes the fact that most materials specified in metric units and necessary for construction of this project may not be commercially available at the time they are required for construction. To this end, the Department has endeavored to convert most dimensions so that existing English items can be supplied where metric items are not available. Therefore, imperial items may be substituted for metric units provided these items conform to the closest English equivalent in size for the specific metric item.”

It is further stated that reinforcing steel and high-strength bolts can be substituted directly as outlined in a table provided in the contract.

In order to support the plan drawings especially of congested reinforcement details in pier tables and abutment areas, so-called “Integrated Detail Drawings” with the three-dimensional appearance of the reinforcement were supplied in electronic format to all bidders through VDOT (VDOT 1997c, pp42ff). Moreover, electronic files of CADD (Computer Aided Design and Drafting) plan drawings were made available to the contractor, as stated on Sheet 2A of the plan drawings.

Shop drawings provide detailed information on all members of the bridge structure. If necessary they contain revisions of the original plan drawings, as e.g. in case of the change in superstructure segment length that is explained in Section 5.2.3.

5.2.7.2 Structural Calculations

Structural Calculations for the Wilson Creek Bridge comprise two comprehensive volumes that were produced by the consulting engineers. Special software for structural analysis of bridge structures was used. The structural calculations comprise calculation of stresses and deflections of the structure during different stages of construction and under various loading conditions. Time-dependent properties of construction materials, i.e. creep and shrinkage of concrete and relaxation of prestressing steel were considered in the calculations. All assumptions that were used in the calculations are listed separately. Complete printouts of all numerical input and output data form the body of these two volumes.

5.2.7.3 Geometry Control Manual

The Geometry Control Manual is a reference guide for the engineers on site. It contains spreadsheets and tables as well as narratives of the erection sequence and control procedures. The consulting engineers' company, Janssen & Spaans Engineering, Inc. produced the Geometry Control Manual for Wilson Creek Bridge. VDOT states on the plan drawings the responsibility of the contractor for the construction means and methods (VDOT 1997c, p81):

“All information shown is for the Contractor’s information only, and the Contractor is responsible for the means and methods used to construct the structure. The Contractor shall submit to the Engineer calculations of the influence of the selected erection sequence, loads, and details on the structure, in accordance with the Project Specifications.”

The Geometry Control Manual is “a procedural guide for the casting and survey control” of the erection sequence with its 307 steps (Janssen & Spaans Engineering, Inc. 1999a, p1):

“The manual describes the theory behind the casting of balanced cantilever bridges using travelers, the geometrical coordinate system and conventions, survey and geometrical control, procedures and methods to be used, and the computer spreadsheet which will provide the erection elevations necessary for determining the casting set-up values for the traveler. Also included are the adjusting procedures to be utilized should the structure, as erected, deviate from

the required alignment by more than 1/1000 of the span length for either vertical profile and/or horizontal alignment.”

The Geometry Control Manual comprises three parts. Book I contains the aforementioned verbal descriptions and geometrical data for the box girder. Geometry data is given for uncambered and cambered elevations, i.e. as final long-term elevations and as elevations increased by a calculated value for construction loads and construction-related processes. A program called GEOM (Geometrical Solution of Highway Bridges) calculated the three-dimensional coordinates by first calculating the elevations along the centerline of the bridge superstructure, and thereafter determining a radial offset for the edges of the box girder (Janssen & Spaans Engineering, Inc. 1999a). Finally, incorporating the slope in the transverse axis gave the final coordinates. With this method, the three-dimensional coordinates for any geometric point of the bridge superstructure were easily determined. Actual measurements will be taken frequently and plotted against the anticipated values to determine any deviations.

Book II contains information and numerical data for construction of cantilevers around Pier 2, which is the highest pier, considering of time-dependent effects during construction operations.

Book III contains the same information for all other cantilever spans (Janssen & Spaans Engineering, Inc. 1999a).

5.2.8 Architectural Considerations

The Wilson Creek Bridge has been designed under consideration of its impact on the surrounding natural environment. Architectural consideration played a major role in giving shape and color to the bridge structure. All piers of the bridge have been given an architectural shaping through implementing a vertical taper on all faces of the rectangular pier shafts. In addition to that, the piers are decorated with natural stone inlays that provide a distinctive vertical accent to the pier faces. At the pier table the stone inlays end and the shape of the tapering pier shaft is blended with the shape of the box girder that tapers in the opposite direction. The overall horizontal lines of the bridge superstructure of several continuous span thus become more articulated. The

slender spans of the superstructure gain additional visual lightness through the varying depth of the box girder. Figure 5-13 shows a rendering of the completed project of two bridges.



Figure 5-13: Rendering of the Completed Project (taken from The Roanoke Times 1999c)

Apart from the bridge piers, the barrier terminal walls at the approaches will also be decorated with natural stone inlays. Railings, according to information from the VDOT site on the World Wide Web (VDOT 1999), were chosen by the Smart Road Citizens Advisory Committee to be Kansas Corral type cast-in-place railings.

The General Notes of the bridge plan drawings give information on the surface finish that the Wilson Creek Bridge will have. The color of substructure and superstructure “shall be Light Chamois, similar to Federal Standard Color No. 595-33717” (VDOT 1997c, p5).

5.3 PROJECT CONSTRUCTION

Having familiarized with the overall project, with the type and dimensions of the bridge to be constructed as well as with the contractual provisions and design of the whole undertaking the following sections are devoted to actual project execution. Descriptions follow the logical order of the construction schedule, leading from initial preparations and construction of foundations and substructure to superstructure erection and supplementary works.

5.3.1 Site Layout and Subsurface Conditions

The overall site location and layout is shown on the site overview plans provided in the first part of the plan drawings. Surveying data for the area of the site is provided. A railway route of the Norfolk-Southern Railroad is running parallel to Ellett Road (Route 723) on the northern end of the construction site and is crossed by another highway bridge structure near the approach to Wilson Creek Bridge.

Wilson Creek is located under the span between Piers 2 and 3 of the bridge. Ellett Road (Route 723) runs between Pier 1 and Pier 2. Both Ellett Road and Wilson Creek are located close to Pier 2. From Ellett Road towards Abutment A and from Pier 4 towards Abutment B the valley slopes more steeply. Access to the main part of the construction site is possible from Ellett Road. Figure 5-14 shows the view from Abutment A to Abutment B with Pier 2 visible on the left. The two crawler-mounted lattice boom cranes that are used to supply material on site can also be seen.



Figure 5-14: Site Overview from Abutment A

Site layout drawings give the exact boundaries of the construction site located under the future bridge structure. Property rights-of-way for adjacent areas are given. Furthermore, the plans give a general overview of boundaries of construction cut and fill areas. The overall baseline in the longitudinal direction of the bridge structure is located between the westbound bridge structure of the Wilson Creek Bridge and a future extension bridge structure for eastbound lanes.

The last pages of the set of plans give information on subsurface conditions. Boring logs are depicted with a scale of 1 to 50 and explained. Altogether, information from ten boring logs is provided. One boring was taken at each abutment of the bridge, as well as two borings per pier foundation, one of them at the edge of the foundation and the other one vertically under the centerline of the pier. VDOT puts a disclaimer on furnishing information on subsurface conditions (VDOT 1997c, pp90ff):

“This subsurface information shown on the boring logs in these plans was obtained with reasonable care and recorded in good faith solely for use by the Department in establishing design controls for the project. The Department has no reason to suspect that such information is not reasonably accurate as an approximate indication of the subsurface conditions at the sites where the borings were taken. The Department does not have any warrant or guarantee that such data can be projected as indicative of conditions beyond the limits of the borings shown; and any such projections by bidders are purely interpretive and altogether speculative. Further, the Department does not in any way guarantee, either expressly or by implication, the sufficiency of the information for bid purposes.

The boring logs are made available to bidders in order that they may have access to subsurface data identical to that which is possessed by the Department, and are not interpreted as a substitute for personal investigation, interpretation and judgment by the bidders.”

Bedrock for Pier 2 was found in little depth underneath ground level, which allowed a change in the erection sequence of piers, as outlined in Section 5.3.5.

5.3.2 Site Preparation

A variety of preparation works were to be carried out prior to actual construction operations on site. The so-called Clear Zone had to be cleared of trees and shrubs and grubbing had to be

performed, as the General Notes for the highway project line out (VDOT 1997b). Clearing of cut and fill areas was also necessary.

A field office with appropriate space and adjacent parking area had to be furnished, set up, and connected to electricity, water, and communication. Construction office trailers are situated south of Pier 2, close to the entrance to the site. The contract documents exactly determine the size, furniture, and other installations for this field office and their maintenance (VDOT 1998). The whole site needed to be enclosed with fencing.

A temporary construction work bridge was needed to cross Wilson Creek between Piers 2 and 3. This work bridge had to be planned and furnished by the Contractor and consisted of solid plates of corrugated sheet metal that rest on girders. It was not allowed to interfere with the flow of the creek (VDOT 1997b), (VDOT 1998). Close to the work bridge a tent to store the prestressing material, i.e. tendon ducts, spiral reinforcement, parts of tremie pipes for conveying concrete, the tendons themselves delivered in large rolls, and anchor plates protected against adverse weather conditions was erected by the contractor. Reinforcement was stored in tagged bundles nearby.

5.3.3 Foundation Construction, Drainage System, and Earthwork

In order to construct foundations for abutments and piers, excavation was necessary. Since solid bedrock was found at little depth beneath ground level in the middle of the valley, relatively small volumes of excavation were necessary for foundations of Pier 2. According to the Project Engineer (PCL 1999d), drilling and blasting were carried out during excavation for the pier foundations. After construction of the foundations, a minimum of 1.00 m backfill above top edge of footings was necessary, as specified in the plan drawings. (VDOT 1997c). Abutment A required a fill to be constructed, as mentioned in Section 5.2.2.1 and rests on piles that reach through this fill.

Further earthwork operations were necessary for construction of the drainage system. Blasting was necessary in parts of the cut for the box culvert. An access road covered with coarse gravel was constructed to permit haulers removing dirt from the excavation areas. During construction a

gap was left in the culvert to allow haulers passing on the temporary haul road. This gap was closed prior to backfilling of the excavation. For construction of the culvert a gravel bed was constructed on which the concrete box culvert was erected with two subsequent placements of concrete. First the bottom slab was cast; secondly walls and top slab were cast between interior and exterior formwork. Upon completion of one section of the culvert the movable form was advanced downhill for casting of the next section. Maximum productivity could be achieved on sections with straight alignment. After backfilling of the box culvert, re-landscaping will be done.

5.3.4 Substructure Construction

The substructure of a bridge consists of the abutments and the piers. Its purpose is to carry the bridge superstructure.

5.3.4.1 Abutments

Abutments are large concrete elements that are supposed to withstand vertical and horizontal forces imposed on the bearings by the bridge superstructure. Due to the large volume of the abutments, several single concrete placements are necessary for their construction. Locations of the horizontal construction joint above the footing and of vertical construction joints in the back wall are determined in detailed plan drawings (VDOT 1997c).

5.3.4.2 Pier Shafts

Pier shafts for the Wilson Creek Bridge are constructed of vertically cast-in-place box segments. The individual segments have a height of about 6.00 m. According to the Project Engineer (PCL 1999d), the heights actually differ to some extent to have about equal concrete placements over

the height of the piers. This is to give the pier erection a more regular cycle pattern with respect to the work crews assigned.

Actual pier construction on the construction site was characterized by about parallel erection of the piers. The Project Engineer (PCL 1999d) lined out that for the Wilson Creek Bridge project erection of the superstructure was anticipated to be time-critical. For this reason, bringing the piers to full height rapidly to allow beginning with cantilevering operations was of importance. Especially Pier 2, including the massive pier table at which cantilevering started, needed to be erected quickly.

Two different sets of formwork were utilized in pier construction. The first set was a starter set for the base segments, the second one a climbing set that comprised four exterior and eight interior panels for rapid assembly and dismantling. The formwork had to be adjusted to pier dimensions at each casting stage because of the vertical taper of the piers. Formwork panels were kept relatively simple for reasons of economy. They consisted of plywood panels that were attached to a stabilizing gridwork of lightweight metal studs and walers. Figure 5-15 schematically shows a pier of the Wilson Creek Bridge during construction, Figure 5-16 shows a real pier for comparison.

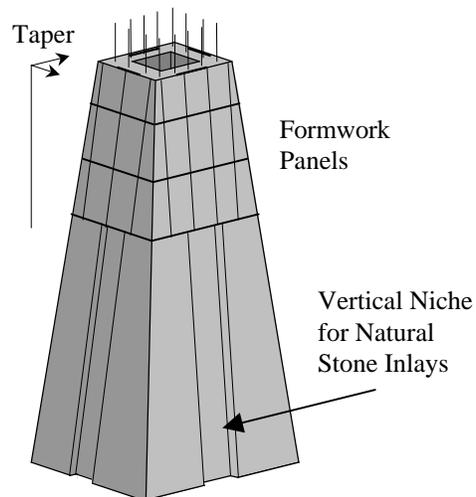


Figure 5-15: Scheme of Pier Erection



Figure 5-16: Pier 3 During Construction with Climbing Formwork

5.3.5 Change in Construction

A comprehensive scheme provided in the last part of the bridge plan drawings shows the erection sequence assumed in designing the superstructure and detailing the mild reinforcement and prestressing tendons. However, VDOT put a disclaimer on information from these schematics (VDOT 1997c, pp81ff):

“The information shown here conveys the assumptions made by the Designer in designing the structure [sic]. All information shown is for the Contractor’s information only, and the Contractor is responsible for the means and methods used to construct the structure. The Contractor shall submit to the Engineer calculations of the influence of the selected erection sequence, loads, and details on the structure, in accordance with the project Specifications.”

In order to optimize the erection sequence for construction of the Wilson Creek Bridge the contractor chose to alter the order in which piers were erected and cantilevering from their pier tables proceeded. The actual order used as approved by the owner was Pier 2 - Pier 3 - Pier 4 - Pier 1. The reasoning for this change is described in the following.

Pier 2 with its shaft height of 41.314 m is the highest pier of the bridge. Tackling this pier first allows beginning cantilevering of one of the main spans of the bridge first and takes it off the critical path of the schedule for the rest of the project. The change in order of pier construction was possible through favorable subsurface conditions at the bottom of the valley. Stable bedrock was found in only little depth beneath ground level at Pier 2.

Construction of Span 1, the northwestern end span of the bridge, is anticipated to provide challenges in accessibility with the crawler-mounted lattice boom crane that supplies construction materials and equipment. Working on the other bridge spans first will allow collection of experience in construction of these and will provide enough time to construct an access road with suitable slope and level ground close to Pier 1 for the crane.

Changing the order of pier erection also required revision of the structural calculations to incorporate the changed overall ages of the cantilever arms about the piers and determine the necessary camber data. Figure 5-17 schematically shows the actual superstructure erection sequence.

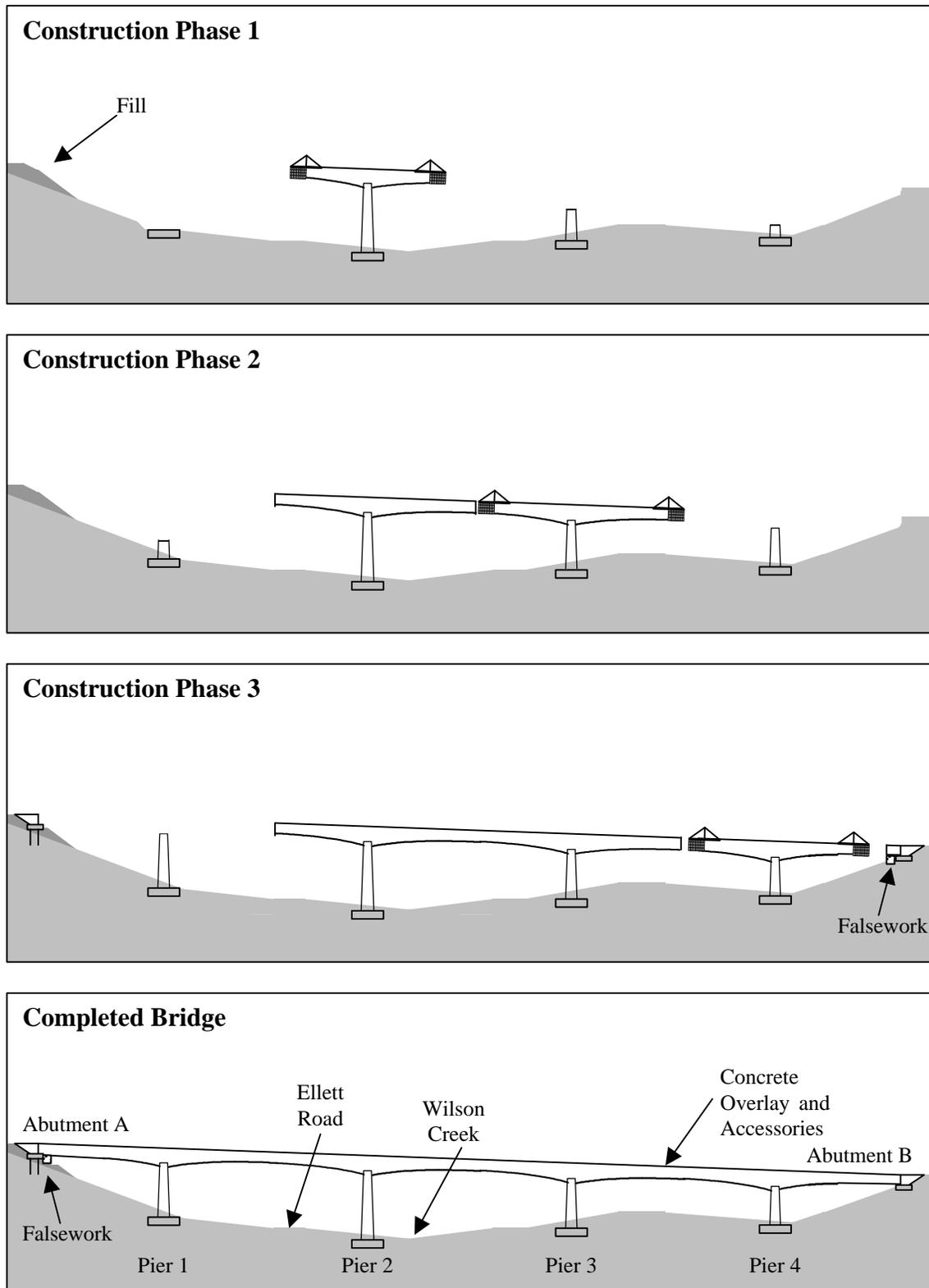


Figure 5-17: Schematic Superstructure Erection Sequence (based on VDOT 1997c)

5.3.6 Superstructure Construction

The bridge superstructure provides a continuous deck for vehicle traffic and rests on the substructure, which in turn is built on the bridge foundations.

5.3.6.1 Pier Tables

In preparation of casting the pier table a frame of metal girders was erected below the future pier table to serve as falsework. This frame then supported work platforms, the large formwork panels that give shape to the pier table, and shoring within the box girder for the top slab forms as well as shoring for the cantilevering top slab flanges. Figure 5-18 shows Pier 3 just prior to erection of the formwork for the pier table.



Figure 5-18: Pier 3 with Metal Falsework for Pier Table Erection

With respect to concrete placement for Pier Table 2 the Project Engineer reported that a changed sequence of placement operations was used (PCL 1999b). Since the volume of concrete in the pier tables is quite large, the placement was broken down into more sections. The whole pier table was cast in four major placements, each consisting of several individual lifts. Construction joints are located between these placements. Single placements included bottom slab, lower sections of webs and diaphragms, upper sections of webs and diaphragms, and top slab. According to the plan drawings so-called Mass Concrete Special Provisions as given in the contract documents are applicable for pier tables (VDOT 1997c). Figure 5-19 shows Pier Table 2. The asymmetry, explained in Section 5.3.8, is clearly visible.



Figure 5-19: Pier Table 2 After Stripping from Formwork

5.3.6.2 Form Travelers

Form travelers as a specialized type of construction equipment for cast-in-place cantilevering have been described in Section 4.2.2.1. They consist of a main structural framework that gives

the form traveler the typical diamond-shaped appearance. Front and back main trusses connect these two frames and are braced with horizontal braces.

The form travelers for construction of the Wilson Creek Bridge are very typical in their layout. A schematic layout of a form traveler can be found in Figure 5-20, an elevation of a form traveler is shown in Figure 5-21. The form traveler provides work platforms at the top and at the bottom part of the segment face as well as a platform under the bottom slab at the back of the segment that is cast. Work platforms also extend along the edges of the cantilevering flanges of the top slab. Thus, optimal accessibility of the newly cast segment is given from all sides.

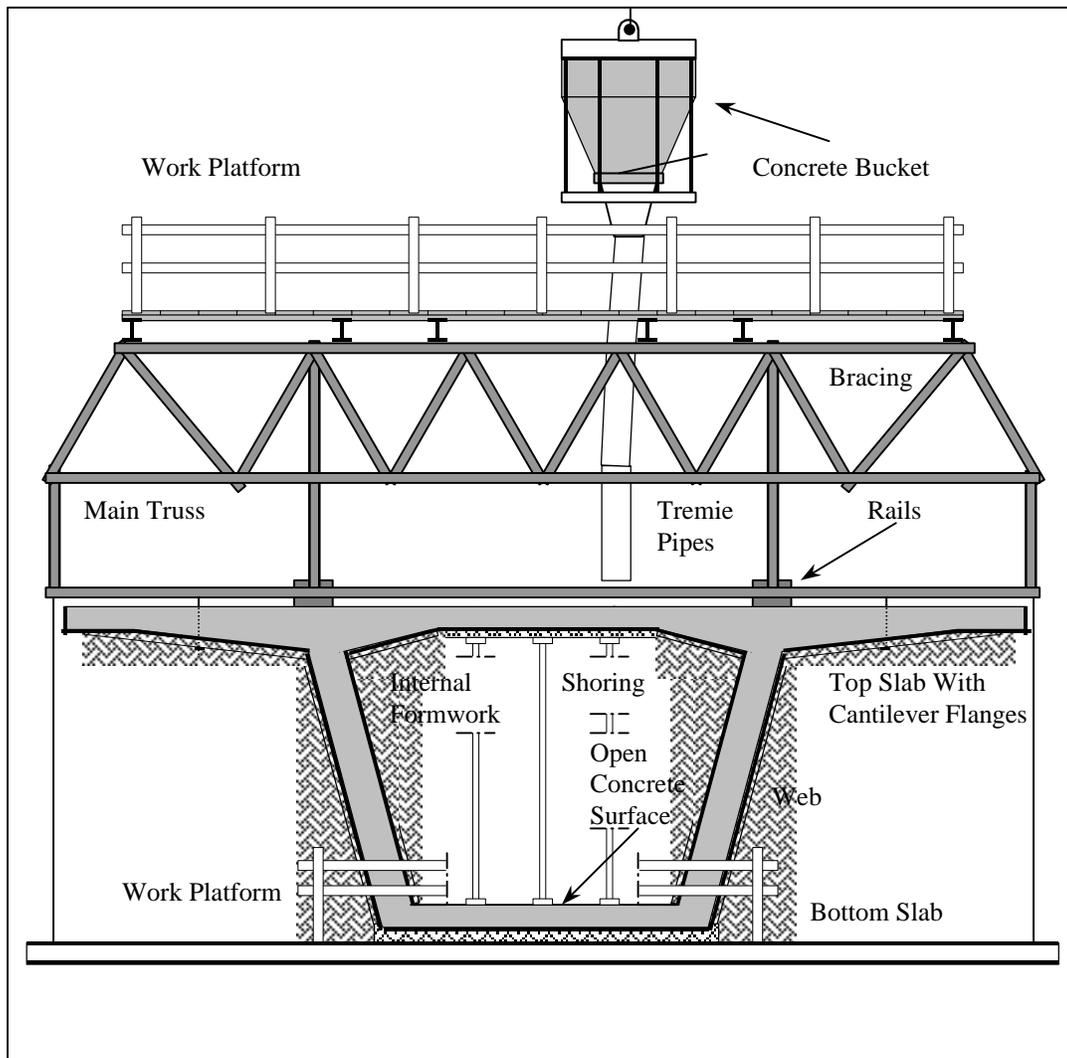


Figure 5-20: Form Traveler Front View

Concrete is supplied to this platform with crane buckets, which would not fit in between the horizontal bracing of the form travelers. Therefore, an additional work platform was set up on top of both form travelers for the Wilson Creek Bridge. This platform is used to prepare and carry out concrete placement into all forms from above. The wooden flooring of this platform has openings through which the concreting crew leads the concrete with so-called tremie pipes.

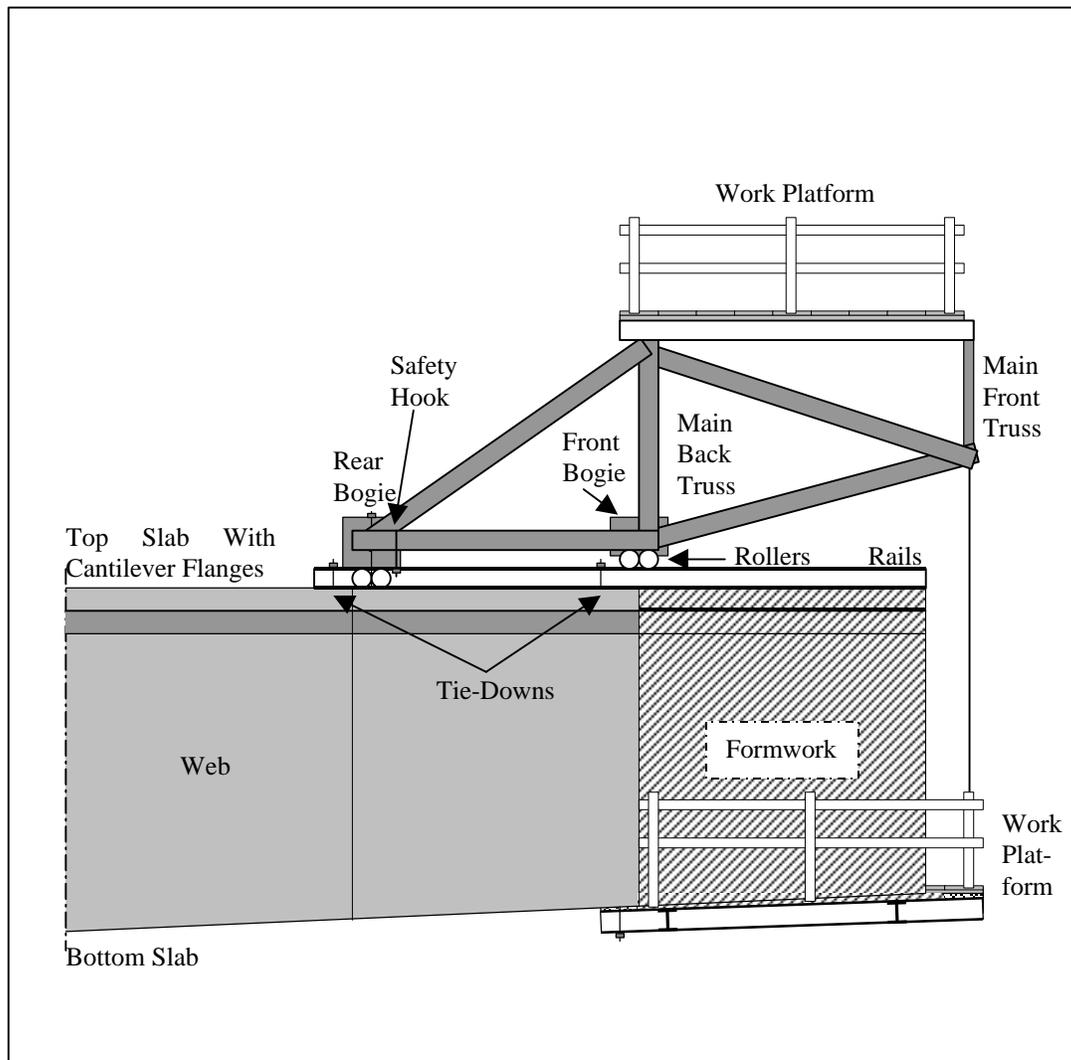


Figure 5-21: Form Traveler Elevation

Long vertical hangers from the transverse trusses are attached to major transverse girders that carry the complete bottom platform beneath the segment. A gridwork of transverse girders and longitudinal beams with bracing in between provides stiffness for the bottom platform. Additionally, the bottom platform is attached to the bottom slab of the previous segment with rods. Formwork for the bottom slab and webs rests on this bottom platform. Formwork for the cantilevering flanges with their rounded haunches is suspended from the traveler by means of hangers.

The interior formwork only consists of wall panels and roof panels, since the top surface of the bottom slab (despite the slight slope of about 6 %) does not require extra formwork. Suspended interior form supports are set up in the box girder under the top slab. They resemble the longitudinal track on the top slab in that the interior wall form supports are also tied to the previous segment and cantilever into the one that is to be cast. The interior form supports are needed to support the formwork underneath the top slab of the box girder and for transverse stiffening of the interior web formwork. Form ties used to keep e.g. web forms from bending apart under the ‘quasi-hydraulic’ pressure of the concrete are threaded rods.

The whole form traveler assembly sits on two pairs of tracks, i.e. rails that are tied down to the segment below with rods. Hollow sleeves are cast into the top slabs of the segments to accommodate these rods. A separate sheet of shop drawings lines out the positions of the many rail and traveler tie-downs.

Rail pairs are located directly above the box girder webs for optimum transfer of forces into the existing bridge superstructure. Three important mechanical elements are necessary for advancement of the form traveler on the rails. The front bogie assembly includes rollers with which the main framework rests on the tip of the rail pairs. The rear bogie assembly includes rollers that grip under the flanges of the rail pairs to tie the form traveler down at its end and prevent it from tipping over the front edge. Additionally, a pull-down system with a pair of strong hooks that are clamped under the flanges of the rail pairs provides additional safety through redundancy of critical elements. No counterweights are used in the form travelers.

Vertical hydraulic pistons are used to move the aforementioned two separate rear tie-down systems to meet the superstructure alignment and to detach the form traveler from its rails whenever necessary during construction operations. Actual form traveler operations in casting the box girder segments are described in Section 5.3.7.

For economic reasons only one set of two form travelers is used in construction of the Wilson Creek Bridge. Hence, this pair of form travelers will be used subsequently on all cantilevering spans around Piers 1 through 4. For this reason, superstructure construction with balanced cantilevering is on the critical path of the overall project schedule.

A noteworthy restriction in overall superstructure shape results from the use of form travelers in construction of the Wilson Creek Bridge. As the formwork panels for the bottom slabs cannot be bent into a continuously curved shape when being adjusted for each element, the overall parabolic shape of the bottom edge of the superstructure is actually a polygonal line.

5.3.6.3 Other Construction Equipment

Apart from the aforementioned form travelers with their work platforms, small aluminum assembly platforms can be lowered from the bridge superstructure to work e.g. on finishing the concrete surface. Metal scaffolding stairwells were installed next to the piers to provide access to the top.

Two Manitowoc 4000 W crawler-mounted lattice boom cranes are used for construction operations. They provide reinforcement, concrete, and any other necessary construction material. Their crawler mounting provides good traction in difficult terrain, but as with any crane, level ground is important. Stable wedges of soil had to be built next to the piers in some cases. Supplying material for construction of the end spans will create a special challenge to the field crew because of the steep slopes of the valley in these areas.

5.3.7 Segment Casting Cycle

The Wilson Creek Bridge is constructed in Balanced Cantilever Construction, using a set of form travelers for cast-in-place construction. The sequence used by the contractor in the casting cycle for a typical superstructure segment of the Wilson Creek Bridge will be described in the following paragraphs. Figure 5-22 shows a schematic representation of the casting cycle based on the description of the actual construction process (PCL 1999d). A more comprehensive schematic of the casting cycle employed is found in Appendix B.

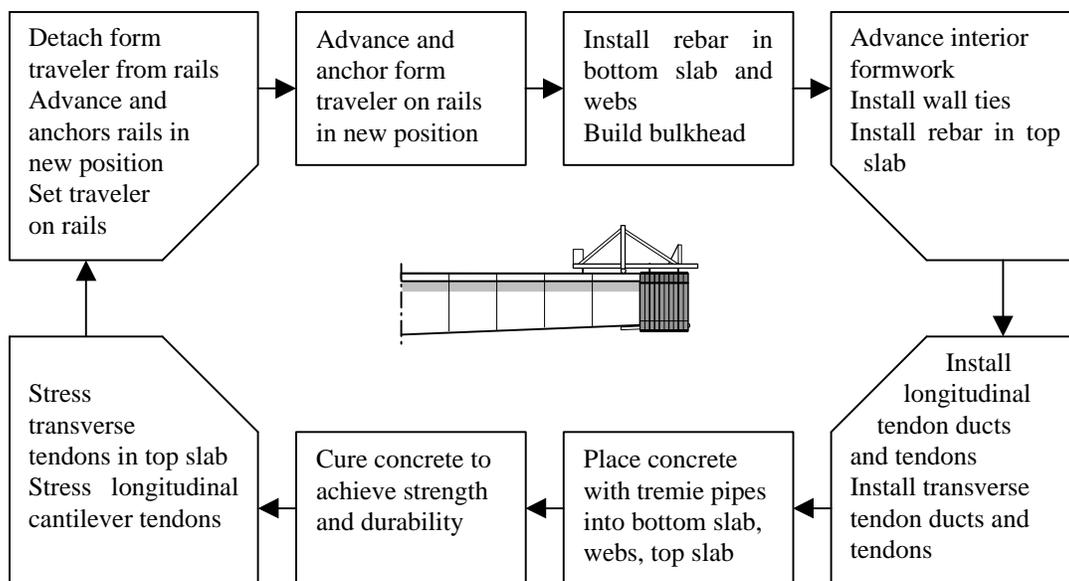


Figure 5-22: Scheme of the Casting Cycle

After a previously cast segment has cured sufficiently for about two days and reached the specified minimum compressive concrete strength of 30 MPa a new cycle begins. First, transverse tendons in the top slab of the segments are stressed. Afterwards the plywood bulkhead forms are stripped from the segment face. Traveler tie-down rods are released and the longitudinal cantilever tendons of the segment are stressed, thus attaching it permanently to the already existing superstructure. Afterwards the form traveler is advanced to the next casting

position and brought to alignment. The outside formwork is advanced as well and trimmed to adjust it to the geometry of the subsequent segment. Formwork panels need to be of high quality plywood, as they will have to withstand all casting cycles for the respective span. Figure 5-23 shows Pier 2 at beginning of cantilevering operations. The setup of both form travelers is visible, as well as the asymmetry by half a segment length to the right.



Figure 5-23: Beginning of Cantilevering Operations about Pier 2

The specific process of form traveler advancement is carried out as follows. After the form traveler tie-downs have been released the rails on which the traveler rests are launched forward and anchored in their position cantilevering above the next segment to be cast. After setting down the traveler on the rails again it is advanced and anchored as well.

On the following day the reinforcement crew begin with installation of reinforcement for the bottom slab and the webs of the box girder segment. Reinforcement is assembled manually, as the form traveler framework and bracing do not provide enough space to lift preassembled

reinforcement cages into place. A carpenter constructs the bulkheads that will prevent the concrete from flowing out of the segment face. The interior formwork is already prepared to match the geometry of the new segment.

The third day of the casting cycle begins with advancement and setting up of the interior forms. Form ties are installed and installation of the reinforcement for bottom slab and the webs is concluded.

On the fourth day of the casting cycle the installation of form ties is finished and assembly of the reinforcement for the top slab begins. In addition to the mild reinforcement the longitudinal and transverse tendon ducts and their tendon strands are installed, but left unstressed.

Day five consists of final preparations for casting of the segment and the actual casting operation. Both Project Engineer and Supervisor control the installed reinforcement and the setup of the formwork prior to casting. Concrete is delivered to site continuously from a nearby batch plant and supplied to the form traveler by crane in buckets. Crane supply is the limiting factor of the superstructure casting operation. Both bottom and top slab of the segment are cast in open forms, as despite their longitudinal and transverse slope, respectively, the concrete has slump small enough to prevent flowing away. Concrete placement operations will be carried out from the work platform on top of the form traveler. Openings in its wooden floor allow tremie pipes to be led into the bottom slab and into the 40-cm wide webs to place the concrete. Flexible pipes of about 20 cm in diameter are inserted between the reinforcement to prevent free falling of the concrete that might lead to its desegregation. The concrete is consolidated with internal concrete vibrators. For construction operations during the Fall and the Winter season it is planned to take special measures for cold-weather concreting. The top slab of segments will be covered with heating blankets for proper curing, bottom slab formwork will be equipped with insulation material, and heaters will be used in the box girder and at the outside faces. A detailed view of the form traveler is provided by Figure 5-24.



Figure 5-24: Form Traveler Detail

Altogether, a five-day cycle is planned for the Wilson Creek Bridge, excluding the time for proper curing of the newly cast segments. Work is performed on both cantilever arms at the same time. However, a time lag of about two days exists between the casting cycles for the two cantilever arms. This allows optimized allocation of work forces, as the crews for formwork setup, reinforcement installation, and concrete placement can alternate between the two cantilever arms, thus reducing downtime. Some reduction in duration of the individual work activities can be expected due to the repetitive nature of the casting cycle and the reduction of segment dimensions towards midspan.

For the Wilson Creek Bridge an alternating stressing sequence was chosen for the longitudinal tendon, i.e. they will be always stressed directly from the side on which the respective newly cast segment is located for more equal prestress distribution. This requires the post-tensioning crew to also alternate between both cantilever tips. Another means of construction could have been to carry out all stressing operations from one side only, e.g. from the Up Station cantilever arm.

5.3.8 Cantilevering Sequence

Cantilevering of the superstructure of the Wilson Creek Bridge began at Pier Table 2 with casting one segment in the Down Station direction. All pier tables are asymmetric to the vertical centerline of their pier by half a segment length. This slight asymmetry in the pier table and the whole balanced cantilevering process has a simple reason. At any point, due to the aforementioned alternating placement of segments, the imbalance between both cantilever arms will be only *half* a segment weight. In other words, the side with the newly cast segment will be half a segment longer until another segment is cast on the other cantilever arm, which in turn makes that side heavier by the weight of half a segment. Thus the overturning moment due to segment imbalance is kept smaller in the superstructure. A schematic of this concept is provided in Figure 5-25.

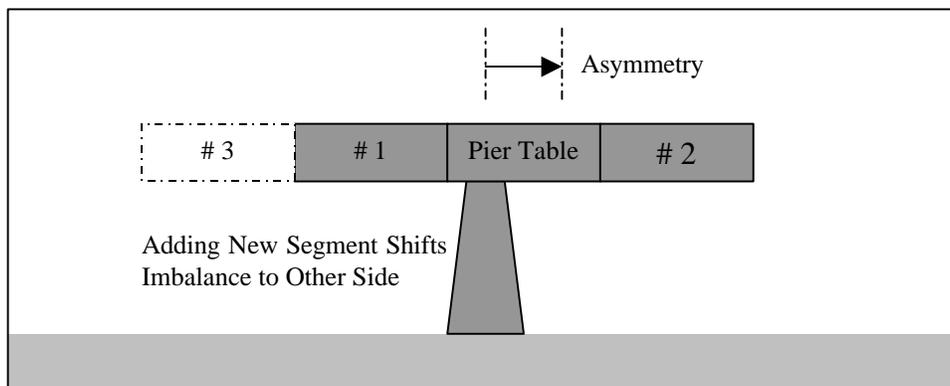


Figure 5-25: Pier Table Asymmetry for Reduction of Overturning Moments

After the cantilever arms about one particular pier are finished, the form travelers will be disassembled and set up at the next pier table to continue with the superstructure erection. Finally, the cantilever arms will be connected at midspan by casting closure segments. Necessary alignment procedures will be performed prior to closure. The erection schemes in the plan drawings inform that all cantilever arms will be jacked apart prior to closure with a jacking force of 1000 kN (VDOT 1997c), accounting for moment redistribution. Cantilever arms will be fixed in the aligned position until the closure concrete has gained sufficient strength (VDOT 1998).

5.3.9 Surveying and Construction Tolerances

A comprehensive surveying program was set up for construction of the Wilson Creek Bridge to ensure that the bridge was built at the planned elevations including camber to account for long-term effects, and at the planned alignment. A fixed baseline for surveying was established on site. Surveying marks have been set as reference points below the future bridge spans.

Surveying points at the corners of pier segments were used to control that the piers were cast exactly vertically. Surveying of the superstructure is a more complex process, since about a dozen points around the circumference of the box girders are measured once cantilevering is proceeding. According to Book I of the Geometry Control Manual, surveying will be performed prior to sunrise to avoid deformations due to thermal gradients in the bridge superstructure (Janssen & Spaans Engineering, Inc. 1999a). Surveying of the actual vertical and horizontal alignment of the bridge superstructure will be performed after each major step of concrete placement. Pairs of surveying points on both arms of the cantilever will be measured to determine overall rotations from pier flexing and shortening, from differential foundation settlements, and from cantilever deflections. In case the alignment deviates from the planned geometry more than construction tolerances permit, correction procedures are outlined in the Geometry Control Manual and supported with an example.

Construction tolerances for the Wilson Creek Bridge are outlined in the contract documents. According to these, casting of a new segment in the superstructure needs to be done within 3 mm tolerance for both elevation and horizontal position (VDOT 1998). Tolerances for individual dimensions of the superstructure segments are provided in the following (VDOT 1998, p146):

<i>“Width of Web</i>	<i>± 6 mm</i>
<i>Depth of Bottom Slab</i>	<i>± 5 mm</i>
<i>Depth of Top Slab</i>	<i>± 5 mm</i>
<i>Overall Depth of Segment</i>	<i>± 5 mm</i>
<i>Overall Width of Segment</i>	<i>± 6 mm</i>
<i>Length of Segment</i>	<i>± 10 mm</i>
<i>Diaphragm Dimensions</i>	<i>± 10 mm</i>

Ends (deviation from a plane per 6 m or 20 feet width or depth) ± 6 mm per 6 meters not to exceed 13 mm

Flat Surface (deviation from a plane at any location) ± 2 mm per meter not to exceed 6 mm

Dimensions from segment to segment shall be adjusted so as to compensate for any deviations within a single segment so that the overall dimensions of each completed span and the entire structure will conform to the dimensions shown in the Plans. The accumulated maximum error should not exceed 1/1000 of the span length for either vertical profile and/or horizontal alignment. Deviations exceeding the tolerances listed above which are discovered during the casting operation shall be identified by after-cast surveys immediately prior to casting the next segment. Corrections for these deviations shall be submitted to the Engineer prior to casting the next segment.”

The Geometry Control Manual for the Wilson Creek Bridge lines out factors that are considered in overall structural analysis to come up deflections and determine the necessary camber (Janssen & Spaans Engineering, Inc. 1999a, p27):

*“*1. Deflection of the travelers under the weight of wet concrete. This is dependent upon the stiffness of the particular traveler system, including rod elongations. For the AVAR traveler, the deflections for the segments are shown on page 44.*

**2. Deflection of the concrete cantilever arms during construction. For each casting of a segment, the weight of the concrete segment and the corresponding post-tensioning forces alters the cantilever deflection.*

3. Deflections of the various cantilevers after removal of the travelers and before continuity is achieved.

4. Short and long-term deflections of the continuous structure, including the effect of superimposed dead loads (barriers, overlay)

5. Short and long-term pier shortenings and foundation settlements.”

A similarly detailed set of requirements on which the above manual is based is provided in the contract documents (VDOT 1998, p142):

“Stages for which theoretical positions of control points are to be computed shall include:

- *Unloaded formwork in position ready to receive concrete. (May involve multiple theoretical positions if cast-in-place concrete is placed in a segment in stages.)*
- *After cast-in-place concrete is placed. (May involve multiple theoretical positions if concrete placement is staged in a segment.)*
- *After each stage of applying post-tensioning.*

The theoretical position shall be computed taking into consideration:

- *Effects of the final profile of the roadway as shown in the Plans.*
- *Effects of structure self-weight along with superimposed construction dead and live loads.*
- *Deflection of form travelers.*
- *Effects of post-tensioning.*
- *Effects of creep and shrinkage.*
- *Effects of non-linear pier behavior.”*

The end of construction with time step 305 is planned to be on day 660 of the project, step 306 is a time step before step 307, which is assumed to be ‘infinity’. The day taken for the state of ‘infinity’ in structural analysis is day 13,750 of the project (Janssen & Spaans Engineering, Inc. 1999a, pp21ff).

5.4 DISCUSSION OF CONSTRUCTION PROCEDURES

In the preceding sections of this chapter the Wilson Creek Bridge project was introduced. Particular attention was given to the casting cycle and the use of form travelers during this procedure. Finally, information on the design background of the bridge was provided.

The outlined construction procedures provide a good example of how concepts outlined in the previous chapters are put into practice. The Geometry Control Manual for the Wilson Creek Bridge summarizes these concepts and prepares them for application in construction operations

on this specific project. Effects of construction loads were taken into consideration in calculation of both short-term and long-term stresses and deflections for each construction stage. Assumptions made in these calculations are stated in the contract documents, in the Geometry Control Manual, and in the printouts of the structural calculations themselves.

The casting cycle used in the Wilson Creek Bridge can be taken as being representative for bridge construction with Balanced Cantilever Construction. A cycle time of about a week is typical for use of form travelers. It is determined predominantly by the strength development of the concrete in the segments and by factors related to equipment utilization such as setting up and adjusting the form travelers for the geometry of the next segment to be cast, and duration of reinforcement installation, of concrete placement, and of stressing operations.

Two major changes in bridge design and construction needed to be included in the calculations. The segment length was changed from 4.50 m to 5.00 m with minor adjustments in pier geometry and closure segments to come up with a more even segment length over the whole span length. Secondly, the order of pier erection was altered to erection of the highest pier first. These changes were implemented to economically optimize the construction operations for cantilevering.

An interesting feature was implemented in pier and segment composition to keep overturning moments due to segment imbalance small. The planned casting cycle had to incorporate crew availability and for this reason had a time lag of about two days between identical work tasks on the two cantilever arms. In order to alleviate effect of this imbalance in adding new segments the superstructure segmentation was designed to be asymmetric by the length of half a segment. Thus at any point in time the two cantilever arms about a particular pier would only be out of balance by the weight of half of segment. Construction loads were anticipated and dealt with in a very elegant way. Summarizing, the case study of the Wilson Creek Bridge ideally serves to underline bridge engineering concepts presented in the theoretical sections of this study.