BRIDGE WATERPROOFING DETAILS

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ABSTRACT

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The objective of this research is to improve the safety margin and redundancy of current waterproofing details used for bridge substructures in PennDOT practice. Based on a literature review, inspection reports, and field visits, the key components of the waterproofing system are studied. Using software analysis and experimental tests, their strength and robustness is analyzed and evaluated based on the damage development and failure mode. The inadequacy in the key components of current waterproofing system is substantiated and remedies to mitigate water leakage are proposed. Executable recommendations are suggested to strengthen the waterproofing details at critical locations and to provide ease of construction and inspection.

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PREFACE

This thesis paper is part of a research project sponsored by the *Pennsylvania Department of Transportation* and the *U.S. Department of Transportation, Federal Highway Administration*.

The author would like to thank Mr. Ronald D. Schreckengost and Ms. Teresa Thompson from PennDOT for providing general guidance for the project and information used in this paper.

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1.0 INTRODUCTION

1.1 OVERVIEW OF ISSUE

Bridges are critical components in transportation networks. Their service quality during their lifespan has a profound effect on the communities connected by them. In Pennsylvania, the highway transportation system consists of about 25,000 state owned bridges and 6,400 locally owned bridges (Pennsylvania Department of Transportation). Therefore, to elongate bridge lifespan and to enhance bridge serviceability is of significant importance for the sustainable growth of Pennsylvania, both economically and environmentally.

For bridges, one of the primary causes of premature serviceability failure is corrosion-related deterioration (Tinnea et al. 2006), which leads to partial or complete bridge closure and costly repairs. To control corrosion-related deterioration, an essential strategy is to limit the access of water, which in Pennsylvania, during the winter contain deicing chemicals, to key structural members. For the bridge substructure, the success of this strategy depends on the strength and redundancy of waterproofing details implemented.

1.2 OBJECTIVE OF RESEARCH

The objective of the project is to remedy water leakage issues at the bridge substructure by analyzing current deficiencies or issues in waterproofing design and construction, proposing executable recommendations with the goal of implementing these recommendations to improve the safety of substructure components and enhance the robustness of the waterproofing system.

This research paper is focused on developing executable implementations to help Pennsylvania Department of Transportation (PennDOT) improve waterproofing practices in design, construction, and inspection with the long term goal of fulfilling of the overall project objective.

To fulfill the research objective, this paper is divided into 3 main parts: A literature survey, field visits and analytical research, and preliminary recommendations; each being briefly described below.

1.2.1 Literature review

The literature review looks into current PennDOT specifications and practice for bridge waterproofing, general guidelines of the American Association of State Highway and Transportation Officials (AASHTO) manual and current bridge waterproofing practice in 3 other states having similar weather patterns to Pennsylvania. In order to enhance current waterproofing practice, a deeper understanding of the working mechanisms and damage development in key components is needed. Therefore in this review, the waterproofing system is broken down to expansion joint, abutment, and drainage. Key components in different waterproofing details are identified and supplemented by preliminary comparisons and evaluations with a focus on issues regarding safety margin and system robustness. Furthermore, inspection practices are also included in this review to analyze the current methodologies in detecting water leakage and damage in waterproofing systems.

1.2.2 Field visits and analytical research

Currently, substantial inadequacy is found in PennDOT practice regarding the bridge waterproofing details. This inadequacy is evidenced by severe water leakage in 5 sample bridges located in District 10-0 of PennDOT, all of which are built after 2008 and adopt the recently-issued PennDOT recommendations for waterproofing during the time of construction. All 5 bridges are visited to observe the bridge waterproofing implemented, record factors that contributed to the leakage of these bridges and record water runoff patterns. Observations are then compared to the inspection reports, and construction or design drawings to find out whether underlying issues are *design* related, *construction* related or a *combination* of both. These are then compared to inspection reports of bridges in other states and along with the design drawings and performance of key components are noted.

After rating the performance of these key components, software based simulation and experimental tests are conducted on them to find out their durability and reliability. The findings are then put in perspective of performance of the waterproofing system to find out weaknesses in design or material, and areas where redundancy is lacking.

1.2.3 Preliminary recommendations

Preliminary recommendations are then suggested based on the results of the literature review, field observations and analytical research, keeping in mind current design methodologies and philosophies of PennDOT. Practicality of implementation, costs, materials used in the components are not looked into in detail and implementation of these recommendations is left as future research.

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

Generally, strategies to combat water-induced corrosion are different for the superstructure and substructure of a bridge. Since structural members in the superstructure are directly exposed to rain and snow, focus is given to use of corrosion-resistant coatings and materials, and efficient and quick drainage systems. However, in substructure components, the deck and waterproofing joints provide most of the necessary protection against direct exposure to rain and snow. However repair or replacement of the substructure is a much more costly endeavor than repair or replacement of the superstructure. Therefore, an efficient and economical strategy is necessary to strengthen the waterproofing system to prevent water from leaking or over-spilling onto the substructure elements.

For the substructure of a bridge, the service quality of the waterproofing system mainly depends upon the functionalities of the following key components:

- **Expansion Joint:** It is a non-structural component designed to accommodate the movement of the deck due to concrete shrinkage and creep, post-tensioning shortening, thermal variations, dead and live loads, wind and seismic loads, and structure settlements. In addition to providing ride comfort, it must prevent runoff water and deicing chemicals from leaking onto bearings, abutments, and other structural elements underneath the bridge deck;
- **Abutment waterproofing:** It is a structural member designed to support the superstructure at the end of the span. In addition to its structural contribution, it incorporates waterproofing features to prevent ground water, surface runoff, and chemicals from coming in contact with the substructural elements;

- **Other Waterproofing and Drainage:** This encompasses other components that allow the expansion joint and abutment waterproofing to work as one cohesive and robust system. The components include waterproofing membranes, coatings, pipes, waterstops and non-expansion joints;

To ensure the service quality of the waterproofing system, these three key components must fulfill their functions during the expected lifespan of the system.

In view of this, the key components of waterproofing system are expected to 1) sustain the designed external and internal loads induced by traffic and weather; 2) endure malfunction or dysfunction of any subcomponent without comprising the overall service quality and operation of the system; and 3) optimize design details so as to achieve efficient construction and low-cost maintenance. To achieve this, safety margin of key elements and redundancy of system must be guaranteed in design and construction. It is also desirable that any dysfunction in the subcomponents can be quickly detected and evaluated in the inspection so as to repair or replace before further deterioration or irreversible damage occurs.

2.2 OVERVIEW OF CURRENT WATERPROOFING PRACTICE

Specifications and recommendations issued by AASHTO serve as the basic guidelines for highway bridge design and construction in North America. For bridge waterproofing details, AASHTO guidelines are referred to in state Department of Transportations' (DOTs) designs. However, these guidelines for performance requirements, to a certain extent, only give general but vague principles without specifics. For example, except for the Modular Bridge Expansion Joint (MBEJ), few structural and functional standards are given to guide the structural design of waterproofing components in other types of joints. Instead, AASHTO allows the state DOTs to develop these specifics and establish their own practices, as long as the basic principles in design and performance are satisfied. This has resulted in different waterproofing details for different states. Currently, Pennsylvania practices for bridge waterproofing details follow PennDOT specifications and recommendations, and comply with general AASHTO guidelines. The PennDOT design manuals and recommendations are as follows:

- PennDOT Design Manual Part 4, Structures, May 2012 Ed. (Pub 15M)

- PennDOT Publication 408/2011
- PennDOT Standards for Bridge Design, Aug. 2012
- PennDOT Standards for Bridge Construction, Aug. 2012
- PennDOT Bridge Safety Inspection Manual, Mar. 2010

In this paper, additional strike-off letters describing the modifications of the waterproofing details are added since they were in effect during the construction of 5 bridges visited as part of the project.

Table 2.1: Weather Data from NOAA (average from 1981-2010)

	1	2	3	4	5	6	7	8	9	10	11	12
Average Monthly Temperature (F)												
Pittsburgh	28.5	31.3	39.8	51.1	60.2	68.9	72.8	71.6	64.3	52.9	43.1	32.5
Boston	29.3	32	38.6	48.4	58.2	68	73.7	72.4	65.2	54.3	45	35
Minneapolis	15.6	20.8	32.7	47.5	59.1	68.7	73.7	71.1	62	48.9	33.7	19.7
Columbus	29.2	32.4	41.5	52.7	62.2	71.2	74.9	73.6	66.4	54.7	44	33.1
Average Monthly Precipitation (in.)												
Pittsburgh	2.69	2.39	2.94	3.11	3.94	4.3	3.83	3.47	3.11	2.29	3.23	2.84
Boston	3.36	3.25	4.32	3.74	3.48	3.68	3.43	3.29	3.44	3.94	3.99	3.78
Minneapolis	0.9	0.76	1.89	2.65	3.36	4.25	4.04	4.29	3.07	2.43	1.76	1.15
Columbus	2.72	2.25	3.02	3.4	4.17	4.01	4.79	3.32	2.84	2.6	3.19	2.96
Average Monthly Snow (in.)												
Pittsburgh	11.8	10.3	7.2	1.5	0	0	0	0	0	0.4	2	8.2
Boston	14	11.3	7.8	1.9	0	0	0	0	0	0	1.3	8.8
Minneapolis	11.7	8.5	10.8	2.8	0	0	0	0	0	0.6	8.9	12.2
Columbus	9.3	6.9	4.2	1	0	0	0	0	0	0.2	0.8	5.2
Monthly Occurrence of Precipitation > 0.01 in. (days)												
Pittsburgh	16.2	13.6	14	13.8	13.3	12.1	10.2	9.8	9.8	10.5	12.8	15.1
Boston	11.3	9.8	11.6	11.2	12	10.8	9.6	9.4	8.6	9.4	10.6	11.6
Minneapolis	8.9	7.4	9.3	10.7	11.5	11.3	10.2	9.7	9.8	9.2	8.7	9.8
Columbus	14	11.4	12.8	13.7	13.9	11.2	10.6	9.2	8.4	9.4	11.4	13.2

In this report, manuals and specifications from MnDOT (Minnesota), ODOT (Ohio), and MassDOT (Massachusetts) are also collected and studied. As listed in Table 2.1 above, these 3 states display weather conditions that are very similar to that of Pennsylvania, characterized by the average monthly temperature, average monthly precipitation, and average monthly snow. Since this project focuses on bridges built recently, the weather data in the last 4 years in these states are also collected and listed in Appendix B (Table B-1 to B-4).

The practices for waterproofing details of MnDOT, ODOT and MassDOT are documented in the following manuals, specifications and drawings:

- MnDOT:
  - MnDOT LRFD Bridge Design Manual, April 2013
  - MnDOT Bridge Construction Manual, November 2005
  - MnDOT 2005 Spec Book Edition
  - MnDOT Bridge Inspection Field Manual, Nov. 2011
  - MnDOT Construction Details Drawings, (Refer to Appendix A)
- ODOT
  - ODOT Bridge Design Manual, January 2013
  - ODOT Construction and Material Specifications, January 2013
  - ODOT Manual of Bridge Inspection, 2010
  - ODOT Construction Details Drawings, (Refer to Appendix A)
- MassDOT
  - MassDOT LRFD Bridge Manual, Part I: Design Guidelines, January 2012
  - MassDOT LRFD Bridge Manual, Part II: Standard Details, December 2011

The waterproofing design and inspection practices, described in the aforementioned manuals and recommendations, will be reviewed by breaking down the design into joints, abutment waterproofing and drainage.

2.3 REVIEW OF EXPANSION JOINTS

In general, AASHTO requires that design and construction of bridge joints must consider the structural performance based on force effects, geometry, materials and maintenance. However, except for the Modular Bridge Expansion Joint (MBEJ), AASHTO does not give specific standards or protocols to design the components of joints. One reason for this vagueness in

AASHTO guidelines is that the structural components of joints, such as the steel extrusion and flexible joint material, are not considered to carry significant load induced by the traffic.

While there are a wide variety of joints available, 5 types of joints are investigated in this review mainly due to their popularity in practice within the 4 states of interest. To have a better understanding of their working mechanisms, a detailed review is given for each type of joint.

2.3.1 Compression Seal Joint

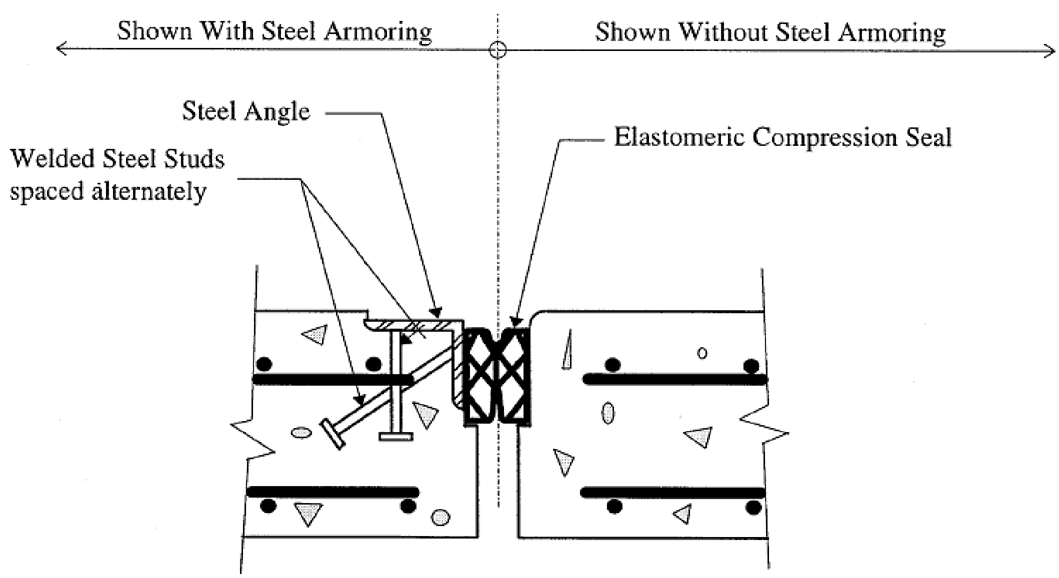


Figure 2.1: Schematic of a compression seal joint (Dornsife, 2000)

Definition: Compression seals (Figure 2.1) are continuous elastomeric sections, with extruded internal web systems, installed within an expansion joint gap to seal the joint effectively against water and debris infiltration. They are held in place by mobilizing *friction* against adjacent vertical joint faces. They are always in a state of compression. Compression seals may be installed against smooth concrete faces or against steel armoring. When installed directly against concrete, polymer concrete nosing material is often used to provide impact resistance. Lubricant-adhesive is typically used to install the seal in its compressed state (Dornsife, 2000).

AASHTO limits use of compression seal with heavy webbing to bridges with a skew angle of less than 20 degrees. The size of joint opening can range from 2.5 to 6.0 inches. Splices and cuts made to the seal on primary roadways are not allowed unless approved by the engineer. AASHTO recommends using this joint in bridges where movement can be accurately predicted. It is also recommended to use saw-cut joint over block-out joint for better joint performance.

Main Components: Compression Seal, Steel Extrusion, Anchorage, Lubricant-adhesive, and Block-out or Saw-cut opening.

Fabrication: If steel armor is used, weld anchorage and armor in shop. Then test assembly before shipping.

Construction Details: If non-armored, saw-cut/form joint opening. If armored, place assembly and temporary supports in block-outs. Cast block-outs. Finally install seal.

Recommended Design Details and Construction Practice in Different States

1. **PennDOT** (Appendix C: Figure C1 – C2)
    - **Steel Extrusion:** N/A
    - **Anchorage Studs:** N/A
    - **Steel Coatings:** N/A
    - **Compression Seal:** Neoprene, AASHTO M220 and ASTM D3542 (Movement Range), minimum movement 1"; no splices permitted
    - **Lubricant:** Conforming to ASTM D4070
    - **Block-out/Joint Opening:** Formed or Sawed joint opening, Sawed using double-bladed, self-propelled concrete saw at saw speed that minimizes spalling
    - **Miscellaneous Details:** Only unarmored compression seal joint is discussed in the design manual. However armored compression seal joint details are given in the Construction Specifications publication of PennDOT (Pub. 408). This is mostly given for maintenance of older bridges.
2. **ODOT** (Appendix C: Figure C3 – C5)
    - **Steel Extrusion:** ASTM A709, Grade 50 or 50W
    - **Anchorage Studs:** End Cross-frame Gusset Plate (ASTM A709, Grade 50 or 50W), Anchor Bar: ASTM A709 (Grade 36, 50 or 50W), Anchor Plates: (ASTM A709, Grade 36, 50 or 50W), and Threaded Rods (ASTM A307 or A709, Grade 36); Galvanize as per ASTM A123
    - **Steel Coatings:** Three-coat paint system consisting of an inorganic zinc prime coat, an epoxy intermediate coat and a urethane finish coat (Not for threaded rods)

- **Compression Seal:** Seal conforming to ASTM D2628, from D.S. Brown (Model CV-4000), or Watson Bowman Acme: Model (WJ-400)
- **Lubricant – Adhesive:** From D.S. Brown (DSB 1520), or Watson Bowman Acme (Wabo®PrimaLub)
- **Block-out/Joint Opening:** Concrete, Compressive Strength – 4.5 Ksi, Cast on site
- **Miscellaneous Details:** *Bridge skew < 15^o*; Non-shrinkage grout; Vent holes in Steel angles.

Comparison between Joints in Different States:

- Steel coatings (paint) used are similar
- ODOT limits skew angle of bridge using this joint to 15^o
- MnDOT uses compression seal only in contraction joints
- MassDOT does not use compression seal joints
- PennDOT does not specify compression seal design; This is left to PennDOT approved manufacturers
- PennDOT does not specify the compressive strength of the concrete used in the block-out in the compression seal joint drawing. However the Construction Specifications publication of PennDOT (Pub. 408) specifies the compressive strength of concrete used for the bridge deck. It may be assumed that the same type of concrete (Class AAAP) be used for the block-out as well.
- Only PennDOT uses a foam filler under the compression seal
- Only ODOT gives a chart showing joint opening size variation during installation; Others leave this to the fabricators

2.3.2 Strip Seal Joint

Definition

An elastomeric strip seal expansion joint system (Figure 2.2) consists of a preformed elastomeric gland *mechanically* locked into metallic edge rails embedded into concrete on each side of an expansion joint gap. Movement is accommodated by unfolding of the elastomeric gland. Steel studs or reinforcing bars are generally welded to the edge rails to facilitate bonding with concrete in formed block-outs. Design of seal gland, lubricant-adhesive used and workmanship are some of the main factors affecting the performance of the strip seal joint (Dornsife, 2000).

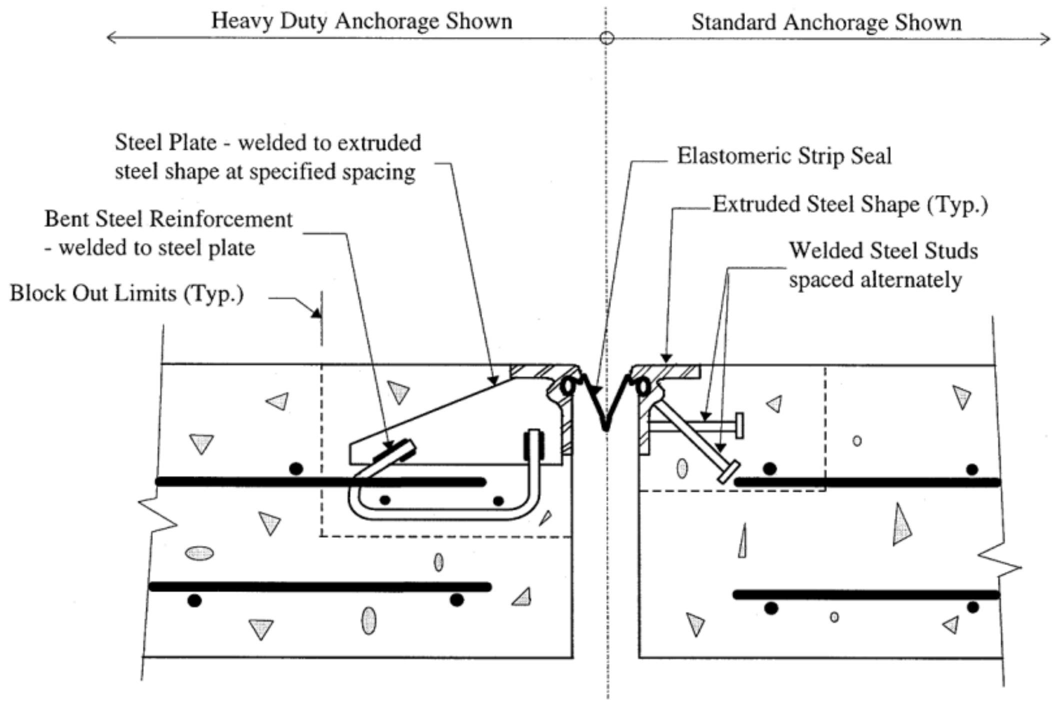


Figure 2.2: Schematic of a Strip Seal Joint (Dornsife, 2000)

AASHTO recommends taking into consideration while selecting the strip seal, exposure to vehicular loads, allowance of complete closure, extension of seal to deck edges rather than bending in curbs or barriers, crown of deck (for lateral drainage of water and debris), shape of gland (to expel debris), and glands without abrupt changes in horizontal or vertical alignments. They maybe spliced only if approved by the engineer.

Main Components: Strip seal, Steel extrusion, Anchorage, Lubricant-Adhesive, and Block-out.

Fabrication: Weld anchorage and steel extrusion in shop and test assembly before shipping.

Construction: Place assembly and temporary supports in block-out, cast block-outs, and install strip seal.

Recommended Design Details and Construction Practice in Different States

1. **PennDOT** (Appendix C: Figure C6 – C7)
    - **Steel Extrusion:** Carbon Steel - AASHTO M270 (ASTM A709), Grade 36, ASTM A36, Grade 50S, ASTM A992

- **Anchorage Studs:** Shear connector studs conforming to AASHTO M169 (ASTM A108)
- **Steel Coatings:**
    - Proprietary, self-curing, inorganic, zinc system, from a manufacturer, consisting of a self-curing, inorganic zinc primer, an epoxy or urethane intermediate coat and an aliphatic urethane finish coat; coats of paint done in shop (or)
    - Galvanize as per material specification (if available) or according to ASTM A153, ASTM B633, or ASTM A392;
- **Strip Seal:** Neoprene, AASHTO M220 and ASTM D3542, minimum movement 3", No splices permitted
- **Lubricant:** Similar to lubricant specification in PennDOT compression seal joint
- **Block-out:** Class AAAP cement concrete, cast on site
- **Miscellaneous Details:** Grind steel edges exposed to traffic or pedestrians to 3/16" minimum

2. **ODOT** (Appendix C: Figure C8 – C11)
    - **Steel Extrusion:** ASTM A709, Grade 50 or 50W for angles, ASTM A709, Grade 36, 50 or 50W for retainer, retainer extruded, machined or hot rolled
    - **Anchorage:** Similar to anchorage specification in ODOT compression seal joint
    - **Steel Coating:** Similar to coating specification in ODOT compression seal joint
    - **Strip Seal:** Extruded Neoprene (no splice allowed), conforming to ASTM D2628
    - **Lubricant – Adhesive:** Moisture curing Polyurethane compound, conforming to ASTM D4070
    - **Block-out:** Concrete, Compressive Strength – 4.5 Ksi, Cast on site
    - **Miscellaneous Details:** *Bridge skew < 60^o***,** non-shrinkage grout and vent holes in steel angles
3. **MassDOT** (Appendix C: Figure C12 – C16)
    - **Steel Extrusion:** Conforming to AASHTO M270, Grade 36, from Watson Bowman Acme (Type A model), or D.S. Brown (Type SSA2 model)
    - **Anchorage:** Conforming to AASHTO M270, Grade 36, from Watson Bowman Acme: Plate/Loop anchor assembly, or D.S. Brown: ½" x 9" studs

- **Steel Coating:** Hot-Dip Galvanized coating
- **Strip Seal:** No splice allowed from Watson Bowman Acme: (SE – 400), or D.S. Brown (A2R – 400)
- **Lubricant – Adhesive:** From Watson Bowman Acme (Wabo®PrimaLub), or D.S. Brown (DSB 1520)
- **Block-out:** Elastomeric Concrete block-out, cast on site

4. **MnDOT** (Appendix C: Figure C17 – C22)
   - **Steel Extrusion:** Low Carbon Steel ASTM A1011/A1011M, Grade 250 (36), Type 2 or High Strength Low Alloy Steel ASTM A709/A709M, Grade 345W (50W)
   - **Anchorage:** Plate and rod, and stud: ½" x 6" bent to 45^o (Same steel as above)
   - **Steel Coating:** Galvanize as per ASTM A123/A123M
   - **Strip seal:** Neoprene, minimum movement 4" (5" for skew over 30^o)
   - **Lubricant-Adhesive:** As per manufacturer's recommendation
   - **Block-out:** Concrete, cast on site
   - **Miscellaneous Details:** Plow finger provided, weld on one side, not to be galvanized, varies with skew and expansion opening

Comparison between Joints in Different States:

- All states explicitly do not allow splicing of strip seal except for MnDOT
- MnDOT uses plow fingers to prevent snow plows when bridge is skewed from 15^o to 50^o
- MassDOT uses an elastomeric concrete block-out
- Only PennDOT and ODOT specify the strength of concrete to be used in the block-out
- PennDOT uses same anchorage for all types of bridges; ODOT uses varying anchorage types for various types of bridges and at curbs and barriers; MnDOT uses different types of anchorage based on location on section of bridge and also on manufacturers
- MassDOT steel extrusion is flush with the pavement surface
- ODOT and MnDOT provide information on joint opening variation during installation

2.3.3 Finger Plate Joint (Tooth Expansion Dam)

Definition:

Finger Plate Joints (Figure 2.3), also called Tooth Expansion Dams in PennDOT practice, are generally fabricated from steel plates and are installed in cantilever or prop cantilever configurations. They accommodate medium to large movement ranges. The steel fingers must be designed to support traffic loads with sufficient stiffness to preclude excessive vibration. Since they do not provide a seal against water, substructure elements are protected from water intrusion and an elastomeric or metallic trough is provided to catch and redirect water and debris runoff (Dornsife, 2000).

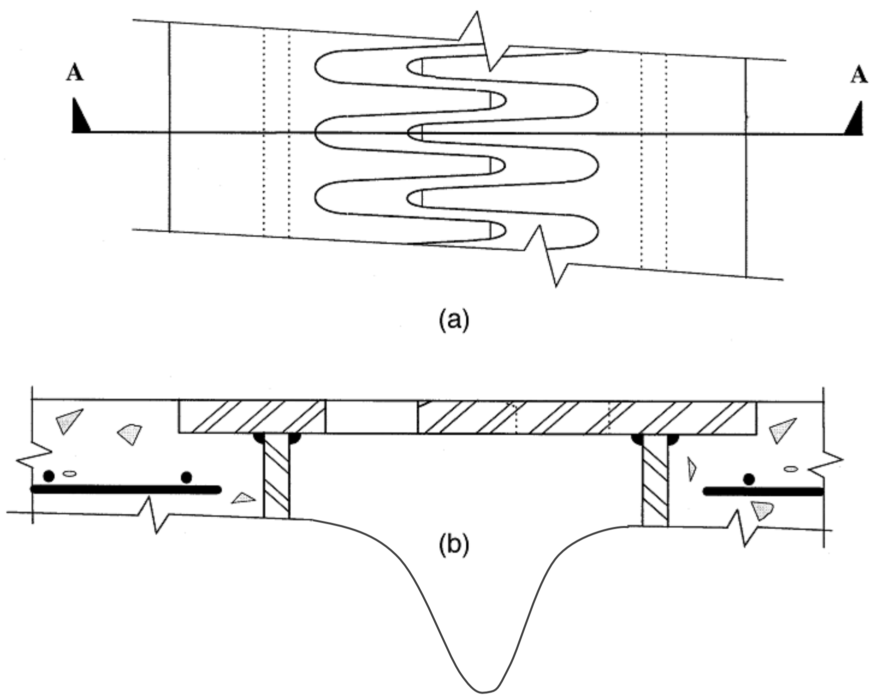


Figure 2.3: Schematic of Steel Finger Joint (Dornsife, 2000)

An effective drainage system is recommended so as to prevent debris accumulation. Care should be given in design of joint so as to prevent debris getting stuck and to prevent issues in joint which may be dangerous to oncoming traffic. AASHTO, MassDOT and MnDOT do not provide any detailed information on Finger Plate Joints.

Main Components: Steel Fingers, Water Trough, Deck protection (steel plate), and Block-out.

Fabrication: Welded and assembled in shop with dam opening preset with shipping angles before shipping.

Construction Details: Erect assembly on site, remove shipping angles, cast joint, and finally install drainage trough

Recommended Design Details and Construction Practice in Different States

1. **PennDOT** (Appendix C: Figure C23 – C25)
    - **Steel Teeth and Plates:** Carbon Steel – AASHTO M 270 (ASTM A 709), Grade 36, with last 1” of tooth tapered
    - **Anchorage:** Conforming to ASTM F593
    - **Steel Coatings:** Similar to coating specification in PennDOT Strip Seal
    - **Rubberized Trough:** Butadiene Acrylonitrile Elastomer material conforming to PennDOT specifications
    - **Block-out:** Class AAAP cement concrete
    - **Miscellaneous Details:** Minimum movement for this type of joint is over 4”; All edges exposed to traffic or pedestrian to be grinded to 3/16” radius
2. **ODOT**
    - **Steel Teeth and Plates:** Prequalified fabricators to fabricate finger device, designed for fatigue and conform to fracture critical requirements
    - **Anchorage:** No information
    - **Steel Coatings:** No information
    - **Rubberized Trough:** Neoprene material
    - **Block-out:** No information
    - **Miscellaneous Details:** Vulcanization of rubber preferred over adhesives

Comparison between Joints in Different States:

- The materials recommended for the rubberized trough differ with both states
- PennDOT details the trough configuration
- ODOT does not provide further information for this type of joint

2.3.4 Asphaltic Plug Joint

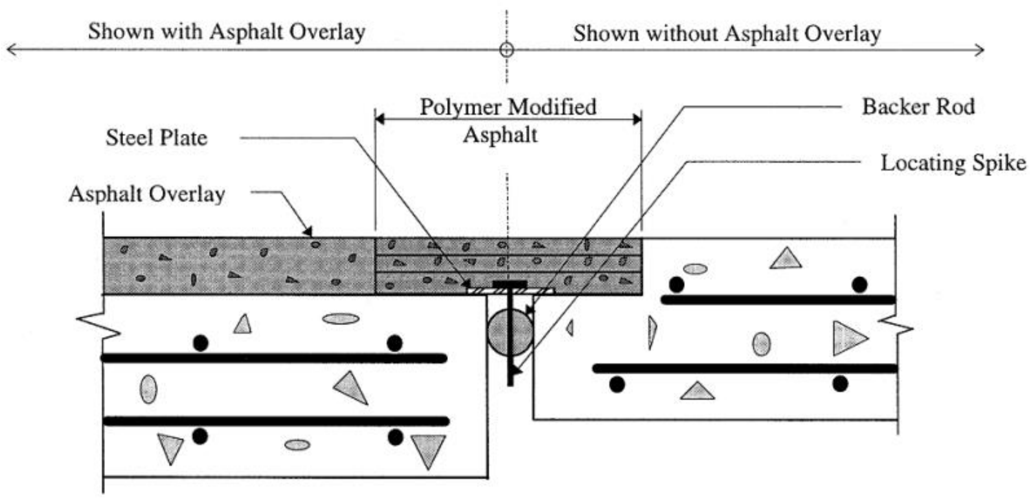


Figure 2.4: Schematic of the asphaltic plug joint (Dornsife, 2000)

Definition

Polymer Modified Asphaltic (PMA) plug joints (Figure 2.4) comprise liquid polymer binder and graded aggregates compacted in preformed block-outs. These joints have been used to accommodate movement ranges up to 2 inches. This expansion joint can be adapted for use with concrete or asphalt bridge deck surfaces (Dornsife, 2000).

AASHTO, PennDOT and MnDOT do not provide any detailed information on Asphaltic plug joint.

Main Components: PMA Plug, Steel Plate, Locating Spike, and Backer Rod

Construction Details: Create block-out of sufficient depth and width, place steel plate and backing rod setup, heat joint material, and apply in layers

Recommended Design Details and Construction Practice in Different States

1. **ODOT** (Appendix C: Figure C26 – C27)
   - **Bridging Plate:** Mild steel 1/8” or ¼” thick plate, 8” wide or 18 gauge aluminum
   - **Backer Rod:** Closed cell foam expansion joint filler
   - **Binder:** Polymer Modified Asphalt, applied at 350 to 390 ^{o}F, conforming to ODOT specifications:
   - **Aggregate:** Crushed Granite or Basalt

- **Miscellaneous Details:** Gaps less than 1/8” to be sealed by pouring hot binder, bigger gaps to be filled with appropriately sized backer rod and to be applied in layers of ¾” to 2½”

2. **MassDOT** (Appendix C: Figure C28 – C29)
   - **Bridging Plate:** ¼” x 8” AASHTO M270, Grade 36 Galvanized Plate,
   - **Backer Rod:** Polyethylene
   - **Binder:** Polymer modified asphalt
   - **Aggregate:** No information
   - **Miscellaneous Details:** Skew of bridge < 30^{o} and maximum 1” one way thermal movement

Comparison between Joints In Different States:

- MassDOT has a skew angle limit for the use of this type of joint
- MassDOT does not provide further information for this type of joint

2.3.5 Modular Bridge Expansion Joint

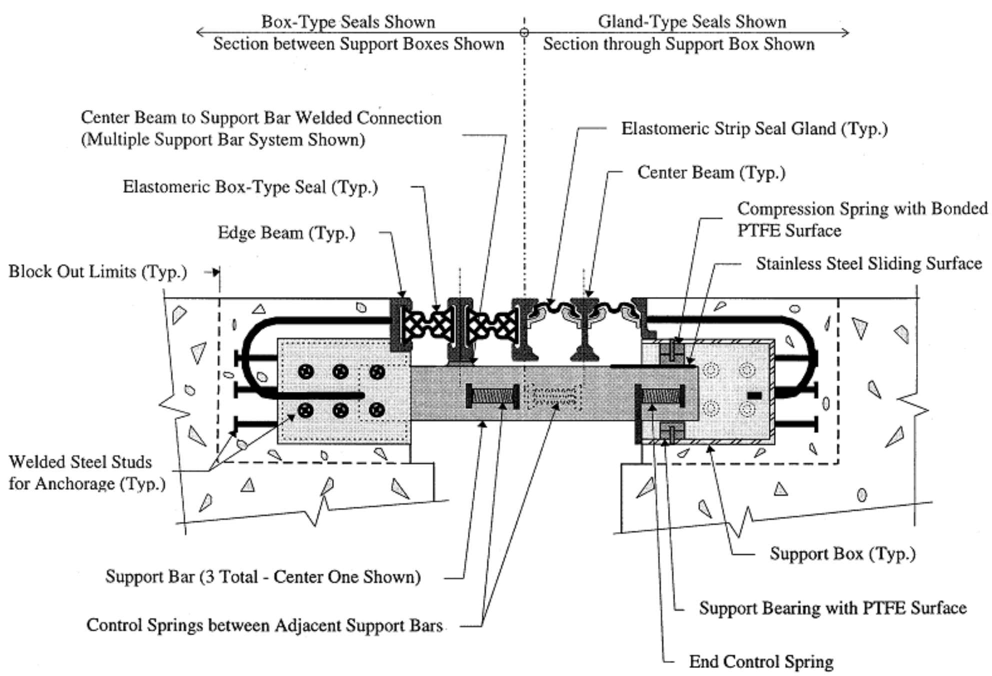


Figure 2.5: Schematic of the asphaltic plug joint (Dornsife, 2000)

Definition

Modular bridge expansion joints (MBEJ; see Figure 2.5) are complex, expensive, structural systems designed to provide watertight wheel load transfer across wide expansion joint openings. They comprise of a series of center beams supported atop support bars. The center beams are oriented parallel to the joint axis while the support bars span parallel to the primary direction of movement. MBEJs can be classified as either single-support bar systems or multiple-support bar systems. In multiple-support bar systems, each center beam is supported by a separate support bar at each support location.

For this complex system, AASHTO gives more specific guidelines in design and construction of MBEJs. The highly repetitive nature of axle loads predisposes MBEJ components and connections to high fatigue susceptibility, particularly at connections of center beam to support bar. Bolted connections have, generally, performed poorly. Welded connections are preferred, but must be carefully designed, fatigue-tested, fabricated, and inspected to assure satisfactory performance and durability (Dornsife, 2000).

The relative complexity in the design of MBEJs causes difficulties in determining the dynamic response of every part within the system. It also makes maintenance more time consuming and expensive. Although complete opening of the joint can expel the debris, it rarely happens (due to over-designing), which makes the system prone to debris accumulation.

PennDOT and MassDOT do not have detailed information in their manuals on MBEJs, therefore the implementation of MBEJs in these 2 states, if allowed, must be referred to AASHTO specifications.

Main Components: Center beam, Support bar, Edge beam and anchorage, Bearings, Springs, Support box, Block-out, and Joint seals.

Fabrication: Assemble and test the MBEJ before shipping and ship MBEJ assembly for required joint opening with appropriate shipping angles.

Construction: Cast block-outs and install MBEJ at proper gap opening corresponding to installation temperature, keeping it fully supported until the block-out sets.

Recommended Design Details and Construction Practice in Different States

1. AASHTO

The MBEJ design should permit movement in six degrees i.e. all three directions and rotation about all three axes. In addition to vertical and horizontal axle loads, snowplow load in snow regions should be considered. Slope and skew of the bridge is to be considered as well. Care should be taken in the interface of the joint anchorage, block-out and deck reinforcement so as to facilitate casting of block-out and placement of joint. Also concrete cover over the support box should be sufficient to prevent reflective cracking.

Structural members in MBEJs, including centerbeams, support bars, connections, bolted and welded splices, and attachments, shall meet the *fracture toughness* requirements in Articles 6.6.2 and *fatigue limit state* requirements in and 6.6.1.2 of the AASHTO LRFD Bridge Design Specifications, 6th Edition manual. Alternative design methods and criteria may be used if tests can show that probability of no fatigue cracks happening over the lifetime of the MBEJs is 97.5%. Typically these joints are designed for an infinite life for little added cost. Critical fatigue points include:

- The connection between the center beams and the support bar
- Connection of any attachments to the center beams and
- Shop and/or field splices in the center beams

The connections maybe welded or bolted. Fillet welded connections have very poor fatigue resistance and should not be allowed. For bolted connections, more than one bolt must be used in the centerbeam. After construction, the joint should be flooded for a minimum of 1 hour to a minimum depth of 3.0 inches. Leakages observed should be repaired.

2. ODOT

In ODOT, MBEJs are to be designed and manufactured by approved fabricator. Since MBEJs fail at connections due to welding and fatigue, spacing of support beams to be limited to 3 feet centers under main load bearing beams unless fatigue testing of welding connection details have been performed to show that greater spacing is acceptable. Also shop and field welds splicing main beams or connections to the main beam should be 100% *non-destructively tested*. Seals should be not be spliced.

3. MnDOT

To be used if bridge cannot be split into 2 and joint expansion requirement is more than 4”. Conventional MBEJ is to be used for normal bridges and swivel MBEJ for skewed bridges.

Summary of MBEJs in Different States:

- Since AASHTO gives detailed information about design and detailing of MBEJs, the other state departments of transportation do not give additional specifics about this joint.

- ODOT has a strict requirement on the quality control of welds on the main beam
- PennDOT and MassDOT make no mention of this joint in their design manuals; so it is not ascertained whether this type of joint is allowed or not.

2.4 REVIEW OF ABUTMENT

Abutment is a part of the substructure of a bridge, which provides vertical support to the superstructure of the bridge. The main parts of an abutment depend on the type used but generally consist of a retaining wall, wing wall, bearing pads, drainage provisions and other waterproofing parts.

Abutments are classified in two broad ways based on connections between the abutment stem and the bridge superstructure:

- Integral/Semi-Integral Abutment: This abutment is monolithically constructed with the bridge superstructure. This type of construction eliminates the need for joints and has a lower maintenance cost. This type of abutment is used on shorter spans of bridges. However the abutment stem has to resist both vertical and lateral forces of the superstructure and is thus difficult to design and has a higher construction cost. If all conditions for construction cannot be met, especially regarding resistance to horizontal movement, semi-integral abutment is used and a joint at the approach slab – roadway interface is provided. This alteration however raises concerns about waterproofing.
- Parapet Abutment: This abutment is constructed separately from the bridge superstructure. Bearings are provided on top of the abutment stem to carry the vertical forces of the superstructure and joints are provided to allow for lateral deflection. Since the abutment is easier to design and construct, construction costs are less but maintenance costs are higher due to the presence of joints.

The main concern for water infiltration in abutments is from the soil. Ground water can go through the backwall of the abutment and cause corrosion to the reinforcement inside resulting in spalling of concrete. Joints at the abutment (especially in parapet abutment) and wingwalls, and abutment seats (bearings) are another area of water infiltration.

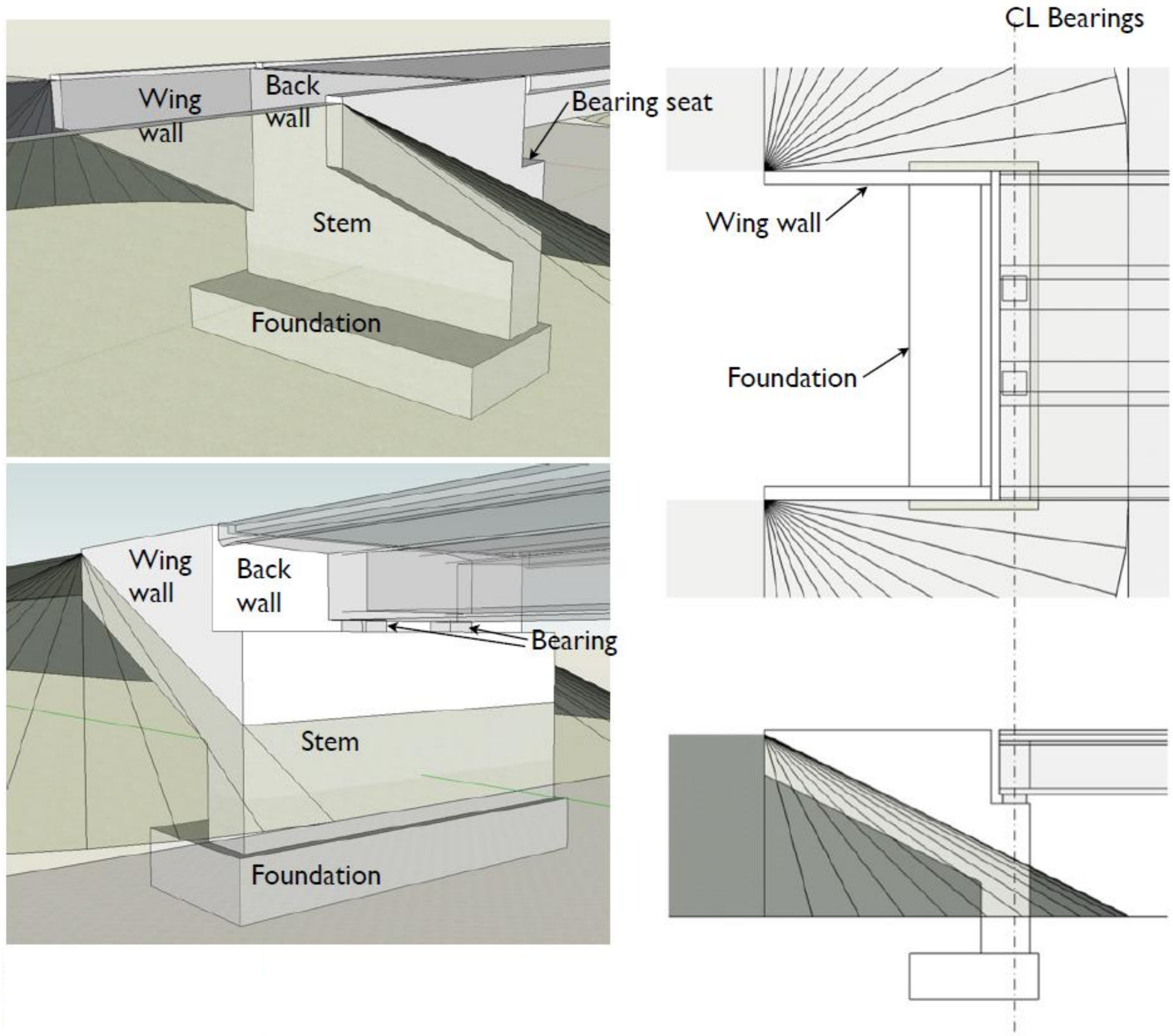


Figure 2.6: Structural components of the substructure (Retrieved from University of Toronto)

2.4.1 Integral/Semi-Integral Abutment:

Except construction joints, there are no other joints in an integral abutment. Therefore, the main concern is preventing ground water from reaching the backwall of the abutment. In the case of Semi-Integral abutments, bearing pads, and expansion joint at the approach slab and roadway interface are of concern.

1. **AASHTO:**
    a. To avoid water intrusion behind abutment, the approach slab should be connected directly to the abutment (not to wingwalls) and appropriate provisions should be made to provide for drainage of any entrapped water
    b. For surfaces against which backfill will be placed, the protective cover shall consist of 0.125 in. hardboard or other material that will furnish equivalent protection from damage due to sharp coarse backfill material.
2. **PennDOT:**
    a. A 2" thick sheet of preformed cellular polystyrene shall be placed against the *entire* area of the back face of the abutment below the bottom of the approach slab. An approved membrane, 2 ft. wide, is placed in between the polystyrene sheet and the back face of the abutment at the construction joint (Appendix C: Figure C30).
    b. The approach slab shall be cast on two layers of 4 mm thick polyethylene sheets (Appendix C: Figure C31). A contraction joint shall be located along the edge of the approach slab at the abutment and filled with an approved sealer. For bridges longer than 150 ft., a strip seal expansion joint is used at the end of the approach slab. A short sleeper slab shall be provided beneath the joint.
    c. If a detached wingwall is used, a neoprene compression seal joint is provided in between the abutment and detached wingwall (Appendix C: Figure C32 – C33).
    d. The expansion devices at the end of the approach slab and adjacent to detached wingwalls shall have a total range of movement equal to twice the abutment thermal movement and shall be a minimum of 2". In case of large bridge spans, other joint types maybe used to accommodate for larger movements.
3. **ODOT:**
    a. The horizontal and vertical joints shall be sealed at the back face of the backwall by use of a 3.0 ft. wide sheet of nylon reinforced neoprene sheeting. The sheeting should only be attached on one side of the joint to allow for the anticipated movement of the integral section (Appendix C: Figure C34 – C36).
    b. Impervious membranes shall not be used for drainage.

c. The joints between superstructure and wingwalls (for semi-integral abutments) are normally filled with 2” performed expansion joint filler material, conforming to AASHTO M153 or M213.

4. **MassDOT:**
   a. AASHTO LRFD Bridge Design Specifications and AASHTO LRFD Bridge Construction Specification to be referred.
   b. Asphaltic bridge joint to be provided at joint between integral abutment and approach slab with 1” diameter PVC drain pipe at the low point of the joint (Appendix C: Figure C37).
   c. Wingwalls to use bituminous damp-waterproofing.
5. **MnDOT:** (Appendix C: Figure C38)
   a. Membrane waterproofing, consisting of rubberized asphalt integrally bonded to polyethylene sheeting, shall be provided for construction joints, contraction joint, doweled cork joints, and on wall joints below ground. Waterproofing is not required at the top of parapet expansion block joint
   b. If construction joint used between abutment and wingwall, use membrane waterproofing.
   c. A 12 mm Polyethylene sheet is to be provided under the approach slab

Comparison between Different States:

- No detailed specifications for the adhesive used to bond the membrane waterproofing and concrete
- Only ODOT gives information specific to Semi-integral abutment
- PennDOT provides waterproofing membrane on the entire backwall of the abutment in addition to another membrane on the construction joint. ODOT and MnDOT provide such waterproofing only at the joints. MassDOT provides no such information.

2.4.2 Parapet Abutment:

The main concern for water infiltration in this type of abutment is from the soil (through the backwall and bearing) and the joint in between the approach slab and bridge deck above the abutment.

1. **AASHTO:**
    a. Contraction joints shall be provided at intervals not exceeding 30 ft. and expansion joints at intervals not exceeding 90 ft. for conventional retaining walls and abutments
    b. Backfills behind abutments and retaining walls shall be drained or, if not designed for earth pressure plus full hydrostatic pressure due to water in backfill; Weep holes or geocomposite panel drains at the wall face do not assure fully drained conditions; Drainage systems should be designed to completely drain the entire retained soil volume behind the retaining wall face.
    c. For surfaces against which backfill will be placed, the protective cover shall consist of 0.125 in. hardboard or other material that will furnish equivalent protection from damage due to sharp coarse backfill material.
    d. The potential for leakage through the wall cannot be ignored where the ground water level exceeds one third of the height of the wall because of the potential for plugging and clogging of openings in the wall with time by migration of soil fines.
2. **PennDOT:** (Appendix C: Figure C39– C41)
    a. Construction joints shall be provided at intervals not exceeding 30 ft. and expansion joints at intervals not exceeding 90 ft. for conventional retaining walls and abutments
    b. For compression seal and strip seal expansion joints at the approach slab – bridge deck interface above the abutment bearing, a waterstop (PVC – Appendix C: Figure C43) is used in addition to foam joint filler (Appendix C: Figure C44 – C46) which is extended to the outside face of the barrier.
    c. For finger plate expansion joints (tooth expansion dams) at the approach slab – bridge deck interface above the abutment bearing, two configurations are possible based on design. A joint with an exposed drain trough or a joint with an integral concrete drain trough using the same rubberized drain trough material mentioned in an earlier section (Appendix C: Figure C47 – C48).
    d. The back face of the abutment shall have 2” preformed cellular polystyrene along with 2 layers of adhesive-backed preformed membrane sheet consisting of a sheet of rubberized asphalt or polymer modified bitumen permanently applied to a polyethylene film or reinforced with a stitch-bonded polyester/polypropylene fabric, or reinforced with a fiberglass mesh (Appendix C: Figure C49).

e. Seepage shall be controlled by installation of a drainage medium (e.g., preformed drainage panels, sand or gravel drains or wick drains) behind the facing with outlets at or near the base of the wall. Drainage panels shall maintain their drainage characteristics under the design earth pressures and surcharge loadings, and shall extend from the base of the wall to a level 1 ft. below the top of the wall. Only Department approved drainage panel materials shall be specified. 6" PVC pipes shall be used as structure foundation drains (Appendix C: Figure C50).

f. 4" diameter formed weep holes shall be provided at a maximum spacing of 15 feet

g. The potential for leakage through the wall should not be counted upon where the ground water level exceeds one third the height of the wall because of the potential for plugging and clogging of openings in the wall with time by migration of soil fines. It is probable that, under such conditions, a wall with continuous vertical elements (i.e., a cutoff wall) constructed with a drainage system designed to handle anticipated flows will be required

3. ODOT:

a. The horizontal and vertical joint shall be sealed at the back face of the backwall by use of a 3 ft. wide sheet of nylon reinforced neoprene sheeting. The sheeting should only be attached on one side of the joint to allow for the anticipated movement of the integral section.

b. Use an impervious fabric across the expansion joints in full height abutments or retaining walls to eliminate leakage.

c. For backwall drainage, the porous backfill immediately behind abutments and retaining walls should be provided. The porous backfill shall be effectively drained by the use of a corrosion resistant pipe system into which water can percolate. The backfill is to be surrounded by a filter fabric, Type A drained using polyethylene pipe conforming to AASHTO M294 (Appendix C: Figure C51).

d. For full-height or spill-thru non-integral type abutments supporting steel beams, steel girders or prestressed I-beams, the drainage of the bearing seat shall be provided by sloping the bearing seat away from the backwall, except at the bearings.

e. If a location demands the use of weep holes, the weep holes through the abutment and retaining walls should be 6 to 12 in. above normal water or ground line. The porous backfill with filter fabric behind the walls should be shown as extending at least 6 in. below the bottom of the weep holes. Weep hole type drainage systems should not be used with concrete slope protection as the flow undermines the concrete protection, ultimately causing its failure.

f. Expansion joints should be provided every 90 ft. unless the total length of wingwalls and breastwall exceeds 90 ft. or if length of breastwall exceeds 90 ft. In this case, a vertical expansion joint should be provided just beyond each side of the superstructure. The expansion joint shall be filled with preformed expansion joint material, conforming to AASHTO M153 or M213, or other suitable compressible material.

g. Impervious membranes shall not be used for drainage.

4. **MassDOT:** (Appendix C: Figure C52 – C54)
   a. AASHTO LRFD Bridge Design Specifications and AASHTO LRFD Bridge Construction Specification to be referred.
   b. Membrane waterproofing or other protective course, minimum 2” thick
   c. 5” thick plastic waterstop for construction joints and 9” waterstop for expansion joints, 8” deep in abutments and wingwalls (Appendix C: Figure C55 – C57)
5. **MnDOT:** (Appendix C: Figure C58 – C60)
   a. Membrane waterproofing, consisting of rubberized asphalt integrally bonded to polyethylene sheeting, shall be provided for construction joints, contraction joints, doweled cork joints, and on wall joints below ground. Waterproofing is not required at the top of parapet expansion block joint.
   b. Abutments and wingwalls (more than 32 feet long) shall have vertical contraction joints at about a 32 foot spacing. Low abutments do not need drainage systems. High abutments shall use 4” drains through wingwalls and back-slopes.

Comparison between Different States:

- MnDOT does not give sufficient detail for design of waterproofing and drainage of abutment. Further review of the detailed implementation of abutment waterproofing in MnDOT will be continued
- PennDOT and ODOT have protective fiber around porous backfill

- PennDOT uses a waterstop below compression seal and strip seal joints, and an integrated drainage
- MassDOT uses a waterstop on the construction and expansion joints in abutments and wingwalls
- No detailed specifications for the adhesive used to bond the membrane waterproofing and concrete face of the abutment

2.5 REVIEW OF DRAINAGE

Definition:

Bridge waterproofing consists of waterproofing membranes, coatings, pipe, and joints which prevent concrete or steel parts of the structure from coming in contact with water. Bridge drainage design addresses removal of water from the bridge deck. These are important for waterproofing system because:

- Efficient removal of water from a bridge deck prevents water accumulation and seepage
- Abutment-level drainage reduces the pressure on the waterproofing membrane and its bonding with concrete
- Safe discharge of water prevents the structure from coming in contact with washed off chemicals and is environment friendly

AASHTO gives no specific design information regarding drainage of deck.

Recommended design details and construction practice in different states

1. **PENNDOT:**
    - **Drainage Pipe:** Connect to existing storm water drain or if impractical, discharge on splash block. For draining the deck, use either standard 8" or 10" diameter NPS steel pipe (ASTM A53) with pipe joints of screwed malleable iron (ASTM A338) or steel welding fittings (ASTM A234) for use with steel pipe. For draining the waterproofing membrane, use PVC pipe (diameter varies with bridge type).
    - **Scupper:** Aluminum curbs or floor drains, coated with an alkaline-resistant bituminous paint.

- **Miscellaneous Detail:** Cleanout plug required when angle of pipe is less than 45^o. At 1 foot from the drain opening, the surface is sloped by ½"

2. **ODOT:**
   - **Drainage Pipe:** For draining the deck, use either galvanized steel pipe or PVC pipe. For connections in steel pipe, use welded joints or clamp-type couplings having ring gasket. In plastic pipe, make connections according to applicable ASTM standards.
   - **Scupper:** Joints of structural steel scuppers to be welded, scupper to be galvanized and anchored using ¾" diameter by 6" long stud conforming to ASTM A108, Grade 1015,1018 or 1020
3. **MassDOT:**
   - **Drainage Pipe:** For draining the deck, use 10"x10" square tube with ASTM A500 Grade A or B steel, hot-dip galvanized. Connections to be two-sided ¼" fillet weld or ¼" PJP weld with a backing seal weld**.** For HMA wearing surface drainage, ¾" diameter pipe, recessed ½" below the top of the slab.
   - **Scupper:** Steel conforming to AASHTO M270 Grade 36, hot-dip galvanized, using ½" diameter and 6" long head anchor for anchorage
4. **MnDOT**
   - **Drainage Pipe:** For draining the deck, use 10"x6" tube or 6"x4" tube of low carbon steel conforming to ASTM A1011/A1011M Grade 250, galvanized either by hot-dipping (ASTM A153) or by a mechanical process (ASTM B695, Class 50, Type I).
   - **Scupper:** Steel conforming to ASTM A1011/A1011M Grade 250, galvanized as per ASTM A123/A123M, using welded steel plates or bolted connections as anchorage
   - **Miscellaneous Detail:** At 1 foot from the drain opening, the surface is sloped by ½"

Comparison between Drainage Practices of Different States:

- PennDOT and ODOT use circular pipes whereas MassDOT and MnDOT use square or rectangular tubes
- ODOT does not give drawings for drainage details
- PennDOT and MassDOT give additional type of joints for drainage of waterproofing membrane and HMA wearing surface respectively

2.6 REVIEW OF INSPECTION PROCEDURES

Although inspection is not an integral part of the waterproofing detail, it is critical as it helps identify and evaluate, in a timely manner, any failure of the waterproofing system under service. In view of this, the current inspection procedures recommended by AASHTO and the state DOTs of interest are reviewed below.

1. AASHTO:

It is a good inspection practice to *clean selected areas* to allow close "hands on" inspection for corrosion, deterioration, or other hidden defects. Debris, vegetation, fungus, marine growth, vines, litter, and numerous other obscuring coverings can accumulate and hide problem areas.

- **Inspection Frequency:** To be inspected at regular intervals not exceeding *24* months unless justified by past reports of good performance history
- **Abutment:**
    - All exposed concrete should be examined for the existence of deterioration and cracks.
    - Examine the abutment drains and weep holes to see if they are functioning properly. Seepage of water at cracks or joints away from the weep holes may indicate an accumulation of water and improper functioning of the weep holes.
    - Inspect joints at abutments, bents, piers, and at hinges. Jamming, unusually large openings, and elevation differentials on opposite sides of the joint are evidences of substructure movement (or bearing failure).
- **Expansion Joints:**
    - Measure expansion joint openings and ambient temperature at easily identifiable locations so that future inspections can establish a record of joint movement over time. Inspect for solid objects (non-compressible) which can become wedged in the joint and prevent joint contraction.
    - On joints without armoring, inspect for proper joint alignment, the presence and condition of any joint sealant material, and for evidence of spalls or "D" cracking in the slab edges, which would prevent proper sealing of the joint.
    - Armored joints without sealant material, such as sliding plate dams or finger joints, should be inspected both above and below deck for the condition of the supports.

Where drainage troughs are provided, check for a build-up of debris that prevents proper drainage and cause spillover onto the superstructure and substructure components, or impede joint movement.

- Sealed armored joints such as strip seals or compression seals should be checked for the presence of defects such as tears, separations, sagging, protrusions, or embedment of foreign material. The underside of all sealed deck joints should be checked for evidence of active joint leakage, shown by water staining of the underlying structural elements. Areas of water staining should be clearly marked on drawings or in the field notes so that future inspections can more accurately assess the extent of active leakage.

- **Drainage:**
  - Examine bridge drainage for both its adequacy and condition.
  - Clogged scuppers and downspouts should be documented and reported.
  - Note drainage through open joints, cracks, or spalls in the curbs or parapets, or other routes that are not intended.
  - Check that the bridge drainage travels through the down spouting and is adequately terminated in drainage facilities or splash blocks. Record any areas of erosion or undermining caused by downspout outfalls.
  - The approach roadway drainage should be directed away from the bridge. Check that roadway drainage facilities adjacent to the bridge are functioning, and that runoff flows into the drainage facilities and does not pond in the roadway or shoulder areas and does not erode the approach fill. Settlement of the approach pavement or fill can significantly alter the roadway profiles and cross slope and redirect water away from the drainage facilities.

2. **PennDOT:**

PennDOT uses a general condition Rating Code for broad structural parts such as deck, superstructure, substructure, walls etc. Condition of specific parts such as expansion joints and drainage are mentioned in the notes. Refer to Table B5 for the Rating Codes.

- **Inspection Frequency:** Depends on condition of bridge. Ideally done once in 24 months. May have to be done more frequently if bridge has weight restrictions, condition rating of 4 or less. Retaining walls are inspected once every 5 years

- **Abutment:** Inspect exposed wall faces, footings and joints for: arching, spalling, movement of joints, corrosion of members, and locations of entrapped water/improper drainage. Inspect drainage facilities in the wall and in the proximity of the wall (above and below the wall) to ensure proper functioning of drainage.
- **Expansion Joints:** Examine underside for evidence of leakage and unusual noise, which may indicate fractured welds or bolts. Debris in joints need cleaning and flushing the deck should be recorded to clean the joint.
- **Drainage:** Drainage deficiencies especially on non-redundant structures shall be given high priority maintenance.

3. **ODOT:**
    - **Inspection Frequency:** Regularly conducted once every year and no more than *18* months and maybe reduced if bridge conditions have deteriorated beyond a point.
    - **Abutment:** Lookout for waterproofing related issues such as structural cracking, delamination, rust staining, efflorescence, leakages and drainage system malfunction; Refer to tables B6 to B8 for ratings of different abutment types and backwall
    - **Expansion Joints:** Examine carefully for signs of leakage, proper opening, anchorage, and deterioration. Refer to Table B9 for guidelines on rating expansion joints.
    - **Drainage:** Examine the drainage system for clogging, ponding, vegetation and adequacy. Refer to Table B10 for guidelines on rating deck drainage.
4. **MassDOT:** No information provided on MassDOT website
5. **MnDOT:**
    - **Inspection Frequency:** No Information
    - **Abutment:** Inspect abutment for concrete deterioration (cracking, leaching, rust staining, delamination or spalling), evidence of deck joint leakage (staining on the abutment face or debris on bearing seat), and functionality of weep holes. Retaining wall abutment condition rating is given in Table B11.
    - **Expansion Joints:** Deck joints should be inspected for leakage, as well as for proper function. Deck joints should be examined for skew, offset, or any evidence that the joint is restricted or is beyond the limits of expansion. Condition rating for strip seal

joint, plow fingers (part of strip seal joint), compression seal joint, finger plate joint and MBEJ are indicated in tables B12 to B15

- **Drainage:** Drainage of deck and approaches should be inspected for inadequacy, clogging, ponding on deck, deterioration of bridge, soil erosion, etc. Table B16 shows condition rating for deck and approach drainage.

Comparison of Inspection Procedures of Different States:

- All routine inspections are primarily visual inspections
- None of state DOTs report debris accumulation over joints as a criteria
- PennDOT gives a relatively general guideline for rating the components of a bridge
- ODOT has the highest inspection frequency of 18 months
- MnDOT has no information on frequency of routine; It is assumed that it follows the AASHTO guidelines as well

2.7 SUMMARY AND PRELIMINARY RECOMMENDATIONS

In this report, the popular waterproofing practices in PennDOT, MnDOT, MASSDOT and ODOT are reviewed and compared by breaking the waterproofing system into its key components which function in very different ways. The key components in different states are studied and compared. Inspection protocols and procedures are also reviewed based on the guidelines and inspection reports collected.

The study shows the vulnerability of the current waterproofing details mainly resulting from the following causes:

1. **Load effects:** Unlike traffic or dead load, external loads affecting the functionality of waterproofing components are not quantified in guidelines, for example, the load caused by debris accumulation or snow plow, or the effect of skew angle. Therefore, the current guidelines do not provide complete loading scenarios for design.
2. **Working pattern:** Although conservative practices are specified for some parts of the abutment, the joint and drainage systems primarily work in a chain system and the strength and serviceability of the system depends on the weakest link.

3. **Safety margin of key components:** Due to incomplete estimates of loads effects, it is next to impossible to design key components for the most unfavorable scenario, neither is it possible to determine the failure mode, which is important for establishing testing protocols to determine the material strength relevant to the failure.
4. **Design and Detailing issues:** Information on design guidelines and detailing in drawings are not complete and many critical decisions are left to the fabricator or contractor.
5. **Inspection technique:** There is a lack of technical approach in accurately monitoring waterproofing details. Conventional visual inspection cannot reach critical locations, which are covered by concrete blocks or buried underground. The highly heterogeneous properties of reinforced concrete and the complex configuration of the waterproofing details also makes it difficult to use ultrasonic and other non-destructive techniques popular in the current inspection and health monitor practice.
6. **Inspection procedure:** In current practice, some important influences are poorly accommodated in the inspection procedure. For example, it is recommended that the bridge be cleaned before inspection. This makes it impossible for the inspection crew to identify and report the pattern and level of debris accumulation in joints. Also it is difficult to ascertain the quality of installation of joint carried out by the contractors.

In view of the aforementioned inadequacies, new strategies must be explored to improve the efficiency and robustness of the waterproofing system. First, it is critical to strengthen the key members to avoid the occurrence of the weakest link due to low safety margin used. Second, it is important to update the current working pattern to a parallel or hybrid system to reinforce robustness and redundancy. Finally, updated inspection schemes equipped with practical and economical approaches to monitor the details need to be explored and implemented.

3.0 FIELD VISITS AND ANALYTICAL RESEARCH

3.1 INTRODUCTION

To substantiate the inadequacy of current waterproofing details in practice and to strengthen the understanding of the system’s working mechanism and its interaction with service conditions, field visits of real bridges are indispensable. The primary goals of field visits are:

- To collect in-situ information about the waterproofing implementation in construction;
- To identify the water runoff patterns and evaluate the efficiency of drainage system;
- To investigate the performance of the key components in waterproofing details under service conditions;
- To detect leakage occurrence and deterioration development in abutments and joints;
- To analyze triggering causes and evaluate failure patterns of the waterproofing system;

5 bridges in PennDOT’s District 10-0 are selected in this study. Among the selected bridges, the oldest one was built in 2009 and the newest one was in 2012. All of the sample bridges adopt the same set of PennDOT design and construction recommendations with regard to waterproofing system. The spans of the bridges range from 25 ft. to 225 ft., and thus cover a broad spectrum of thermal expansions that the constructed expansion joints may experience during the service. The skew angles of the bridges range from 45 to 90 degrees, providing in-situ information on the effect of skew angle on joints. Two of the five bridges are in conjunction with major highways; the other three are over small creeks connecting local avenues. This will help in evaluation of performance of key components under varying traffic densities. Water leakage is reported in the inspection reports for all five bridges. This gives the research team an opportunity to obtain the in-situ information of failure mechanism and failure development of waterproofing details. The 5 bridges are given below along with their year of construction:

1. 10-3025-0020-0204 *Little Creek Road Bridge* – 2010

2. 10-0528-0310-1368 *Prospect #1 Bridge* – 2009
3. 10-0038-0100-0000 *SW of Boydstown* – 2012
4. 10-0038-0200-0129 *Little Connoquenessing Bridge* – 2012
5. 33-1011-0040-0572 *Beechton Bridge* – 2011

To fully exploit the selected sample bridges, three field visits are made, under different weather conditions, for the selected bridges:

- The first field visit is conducted on a sunny day with the intention of recording the current state of waterproofing system in place and finding signs of leakage that may have occurred. Pictures are taken and the accompanying PennDOT engineers are interviewed to find out more detailed information about issues with the bridges.
- The second field visit is held two days after a heavy rain. Four of the five bridges and a new construction site are visited. Signs of leakage are clearly visible on the abutment seats and backwalls. In the construction site, the in-situ implementation of waterproofing details at the deck-approach slab interface is recorded.
- The third field visit is conducted on a rainy day. The primary aims of this field visit is to record water runoff patterns, to check the efficiency of the drainage systems, and to observe the occurrence of water leakage.

The information collected from field visits, supplemented by the information from inspection reports, will be analyzed to give a preliminary evaluation of the performance of current waterproofing system and to identify the cause of failure and dysfunction. This will be detailed in the next chapter.

In order to have a comprehensive comparison with the practice in other states, “virtual” field visits are conducted for the sample bridges located in Minnesota and Massachusetts as well as representative bridges with Integral abutments in Pennsylvania by taking advantage of satellite images from Google Maps, when available. Based on these images, realistic estimations of surrounding topography and traffic condition may be made. These bridges are selected based on similar criteria, i.e., structural type, implementation of waterproofing system, availability of inspection reports and so on. Limited by the access to the inspection reports, the following bridges are selected for the “virtual” field visits:

- One bridge with Integral abutments in Pennsylvania
- Four bridges in Massachusetts

- Seven bridges in Minnesota

Similarly, the collected information in the "virtual" visits will be supplemented by the inspection reports, which will play a more important role here than the real field visits. Study based on these "virtual" field visits will provide valuable information for evaluation of the waterproofing practice in other states. Furthermore, general information with respect to waterproofing details from Illinois and New York State are referred to in the preliminary evaluation, although detailed inspection reports are not available from these two states.

To complement the field observations, software based research and experimental tests are conducted. The objectives of these are:

- To find out the safety factor of the waterproofing component
- To see the performance of individual components when subject to stresses within or beyond required parameters

The parameters chosen for the analysis are based on weather conditions in Pennsylvania, and PennDOT design standards and recommendations. Inferences of the results of this research will be discussed in the next chapter.

3.2 FIELD VISIT OF BRIDGES IN PENNSYLVANIA

Five representative bridges in District 10-0 are selected for field visit in this study. Some of the main characteristics of these bridges are as follows:

- All the bridges have retaining walls as abutments and are skewed;
- Three of the five bridges use compression seal joints. The other two bridges use only silicone sealant and neoprene closed cell sponge as joint material;
- The bridge decks using concrete wearing surfaces are adjoined by approach slabs having a hot-mix asphalt (HMA) wearing surface;
- Three of the bridges connect over a water stream (small creek) and the other two connect over a roadway carrying heavy traffic;
- Two of the bridges are rehabilitated bridges using existing parts of the retaining walls from old bridges; while other three were new when they were built.

Three field visits are made for each bridge, except for Beechton Bridge, for which the second field visit is skipped due to time constraints. In the following sections, the observations made in the field visits will be delineated for each bridge.

3.2.1 10-3025-0020-0204 Little Creek Road Bridge

Figure 3.1: Little Creek Road Bridge

3.2.1.1 Bridge Overview:

This bridge, connects Little Creek Road, is located on Interstate 79 and was built in 2010 (Figure 3.1). The deck is skewed at an angle of 70^{o} and has no surface drains. This bridge has 2 spans, being 105 ft. and 120 ft. long respectively (Appendix C: Figure C61). The bridge contains expansion joints at both ends and is fixed at the pier at mid-span. For the expansion joints, a 1.625 in. compression seal is used for a 0.5 in movement classification (Appendix C: Figure C62 – C65). Based on the design blueprint, waterproofing membranes are extended from the top of the beam to 6 – 12 in. below the bridge seat (Appendix C: Figure C66). The abutment is a retaining wall and has a keyed construction joint near the center of the wall (Appendix C: Figure C67).

3.2.1.2 Bridge Inspection Report

Water leakage was observed on this bridge in an inspection conducted by PennDOT inspectors one year after the bridge was constructed. The sealant was found to have cracked with minor water seepage observed. It was recommended that joints be saw-cut and resealed. The information of abutment waterproofing system is not explicitly available in this inspection report. Note: The inspection report is provided by PennDOT and was conducted on 12/19/2011.

3.2.1.3 Observations in Field Visits

Three field visits are conducted for this bridge. The following observations are made during the visits:

- Expansion Joints: Cracking and erosion of the edges in contact with the sealant are observed in field visits (Appendix C: Figure C68 – C69). Spalling and damage of sealant can be identified by visual inspection (Appendix C: Figure C70). Difference in the level of the opposing sides of expansion joint is conspicuous (Appendix C: Figure C71).
- Abutment and Abutment Seat: Substantial water leakage is found at abutment seats as well as the construction joints between the beam and shear block, and in between the bridge deck slab and the shear wall, in both second and third visits (Appendix C: Figure C72 – C74). However, no water leakage is found at the location of construction joint on the abutment.
- Drainage System: No water accumulation (pond) is found in the third field visit. However, the uneven settlement at the expansion joints disturbs the camber at the joints, and thus detours the discharge path of the water (Appendix C: Figure C75). There is water runoff observed on the deck at the east side joint, although no water runoff is observed on the deck at the west side joint. Despite the severe water leakage found at the abutment seat, no water flow stains are observed from the abutment weep holes in both second and third visits.

3.2.1.4 Summary and Evaluation:

The primary cause of the water leakage in this bridge is the expansion joints. The lack of water runoff on the deck at the west side joint suggests that most of it seeps into the joint. The leakage observed at the construction joint between the beam and shear block suggest that the membrane needs to be extended to the bridge deck slab (Appendix C: Figure C76). Additionally, uneven settlement of the two opposing sides of the joint facilitates debris accumulation which exposes the joint to traffic loads. This uneven settlement is primarily due to the material mismatch between HMA surfaced approach slab and concrete deck.

The wide-range water leakage found from the construction joints in beams implies that there exist quality control problems during concrete casting. Although no leakage is found at the construction joint of the abutment, the damage of abutment waterproofing membrane at the abutment seat cannot be precluded. Due to its inaccessibility, an accurate evaluation of it is difficult as it may be obscured by leakage from the joints.

The drainage system on the deck, using slope of the deck, works properly except for the disturbance of uneven settlement at the expansion joints. The abutment drainage system also seems to work efficiently. The ground water is drained away from the abutment so that there is no water flow found in the weep holes.

3.2.2 10-0528-0310-1368 Prospect #1 Bridge

3.2.2.1 Bridge Overview

This bridge connects Prospect Road, is located over New Castle road and was built in 2009 (Figure 3.2). The deck is skewed at an angle of 70^{o} and has no surface drains. This deck has only one span of about 104 ft. long, containing an expansion joint at one end (Appendix C: Figure C77). A compression seal, 1.5 in. wide for 1 in. movement classification, is used as expansion joint material (Appendix C: Figure C78). The abutment is a retaining wall and has a construction joint near the center (Appendix C: Figure C79).

Figure 3.2: Prospect #1 Bridge

3.2.2.2 Bridge Inspection Report

Heavy water leakage was observed on this bridge in an inspection conducted by PennDOT inspectors three years after the bridge was constructed. Since the joints appear to be in good condition visually, leakage is thought to originate from the backwall. Note: The inspection report is provided by PennDOT and was conducted on 09/12/2012.

3.2.2.3 Observations in Field Visits

Three field visits are conducted for this bridge. The following observations are made during the visits:

- Expansion Joints: Moderate debris accumulation is observed in the expansion joint during the first and second field visits (Appendix C: Figure C80). Severe debris accumulation is observed on the expansion joint during the third field visit (Appendix C: Figure C81). The source of this debris increase is due to recent maintenance works carried out by PennDOT on the HMA wearing surface of the adjoining approach slab and road. The concrete edge of the joint has deteriorated at certain locations (Appendix C: Figure C82).
- Abutment and Abutment Seat: There is leakage observed in the third visit at the abutment seat along the entire length of both abutments (Appendix C: Figure C83). Leakage increases in severity near the ends of the abutment and has local increases in between beams (Appendix C: Figure C84). The observations made in the first field visit seem to indicate that the leakage originates from either the joint or the back wall because a water trail is visible from the top of the beam and there is moisture on the surface of the abutment seat (Appendix C: Figure C85).
- Drainage System: Due to the addition of a layer on the approach slab from maintenance works carried out, and due to debris accumulation along both the edges of the deck, water flow is hindered near the ends of the deck (Appendix C: Figure C86). Water staining is observed in the outer weep holes but not the inner ones (Appendix C: Figure C83).

3.2.2.4 Summary and Evaluation:

The primary cause of the water leakage in this bridge is mostly the joints. This is mainly due to failure of the edge of concrete on the approach slab side and is evident by observing higher amounts of leakage near the ends of the abutments (deck cross-slope prevents water from sitting near the middle area of the deck).

However water leakage from the abutment backwall cannot be ruled out because water leakage is also found at the center portion of the abutment seat, above which the joint looks fine and water efficiently discharges due to deck cross-slope. Water entering from the sloped backfill at the wingwalls may be finding their way to the back wall and some might be leaking out through the abutment seat before finding its way out via the weep holes.

The drainage system on the deck works properly except the accumulation of debris along the edges and ends of the deck causing water ponding. The discharge of water from the weep holes only, in the outer areas, may be due to the slope of the backfill discharging water away from the center. This indicates that the weep holes are working properly and that water leakage issue from the back of the abutment is mitigated.

3.2.3 10-0038-0100-0000 SW of Boydstown

Figure 3.3: SW of Boydstown

3.2.3.1 Bridge Overview

This bridge connects Oneida Valley Road, is located over Pine Run and was built in 2012 (Figure 3.3). The deck is skewed at an angle of 60^o and has no surface drains. This deck has only one span of about 25 ft. long, containing an expansion joint at one end (Appendix C: Figure C87). A compression seal, 1.625 in. wide for 0.5 in. movement classification, is used as expansion joint material. This seal is buried under a 4 in. superpave asphalt overlay (Appendix C: Figure C88 and C89). The abutment is a retaining wall and has a construction joint near the middle. This bridge is rehabilitated by re-facing the existing abutment and adding a new concrete header (Appendix C: Figure C90).

3.2.3.2 Bridge Inspection Report

Signs of water leakage were observed in the abutment in an inspection performed by PennDOT inspectors a few months after construction. The joints seem to be in good condition. Therefore, it implies that water leakage originates from the backside of the abutment, although the exact location cannot be ascertained. Note: The inspection report is provided by PennDOT and was conducted on 11/06/2012.

3.2.3.3 Observations in Field Visits

Three field visits are conducted for this bridge. The following observations are made during the visits:

- Expansion Joints: Joints seem to be in good condition but there are initial signs of deterioration of the edge along the seal. The silicone sealant at certain areas has broken (Appendix C: Figure C91). The condition of the underlying compression seal is unknown as it is inaccessible for visual inspection.
- Abutment and Abutment Seat: Leakage is observed on the first beam from the right on the expansion side abutment (Appendix C: Figure 92. A long crack (with leakage) is observed on the fixed end in between the first and second beams from the left (Appendix C: Figure C93). Leakage is observed through other cracks (having efflorescence) in the lower portion of the abutment wall and seems to originate from behind the abutment at the interface of the old and new abutment parts. Leakage is also visible especially at the construction joint on the abutment (Appendix C: Figure C94).
- Drainage System: Debris accumulation, consisting mostly of silt, can be seen along the edge of the deck (Appendix C: Figure C95). This may be due to the insufficient longitudinal slope of the deck. Two 1 in. weep holes are found on the west side abutment and two 4 in. weep holes on the east side abutment. All weep holes are operational. However silt deposits are found in the 4 in. weep holes (Appendix C: Figure C96).

3.2.3.4 Summary and Evaluation

The main cause of leakage in this bridge seems to originate from the backwall at the abutment seat, construction joint and interface where the old and new abutment sections meet. This is mostly due to inadequate waterproofing at these locations. Some cracks seem to propagate throughout the height of the abutment and show signs of leakage as well. These cracks also seem to originate from the interface between the old and new abutment. The cause of these cracks may be attributed to the differential shrinkage between the old and new concrete and efflorescence, leading to increase in the size and propagation of cracks. For this abutment, there is no waterproofing membrane and waterstop are used for the construction joint, or for the old-new concrete interface. For the abutment seat, only waterstop is applied. The absence of waterproofing membrane and waterstop dramatically lowers the redundancy of the waterproofing system.

Limited by the accessibility to visual inspection, the source of leakage in the abutment seat cannot be determined whether it is from the back of the seat area or from the compression joint. The waterproofing membrane serving as a backup for the compression joint is badly implemented. It is glued onto the bridge deck and then extended to approach slab, a wrong implementation which is similar to that of Little Creek Bridge. This membrane can be easily peeled off because it cannot sustain the thermal movement associated with the bridge deck.

Silt accumulation in the weep holes could indicate reduced efficiency of drainage of backwall of abutment due to clogging of drainage medium. For the deck drainage, the slope provided seems to be insufficient. The water runoff does not seem to have sufficient velocity to take the silt off the deck off the bridge.

3.2.4 10-0038-0200-0129 Little Connoquenessing Bridge

3.2.4.1 Bridge Overview

This bridge connects Oneida Valley Road, is located over Connoquenessing Creek and was built in 2012 (Figure 3.4). The deck is skewed at an angle of 45^{o} and has no surface drains. This deck has only one span, around 34 ft. long, containing an expansion joint at one end (Appendix C: Figure C97). Neoprene compression seal, for 0.5 in. movement, along with a 0.5 in. neoprene closed cell sponge is used as expansion joint material (Appendix C: Figure C98and C99). The abutment is a retaining wall and has a keyed construction joint near the center of the wall (Appendix C: Figure C100).

Figure 3.4: Connoquenessing bridge

3.2.4.2 Bridge Inspection Report

In an inspection carried out by PennDOT engineers few months after construction, both the abutments showed signs of leakage, even though the joints seemed to be in good condition. This suggests leakage originates from the backwall. Note: The inspection report is provided by PennDOT and was conducted on 10/29/2012.

3.2.4.3 Observations in Field Visits

Three field visits are conducted for this bridge. The following observations are made during the visits:

- Expansion Joints: The joints seem to be in good condition. There is no debris accumulation on the joints. However cracks are visible in the HMA surface edge adjacent to the joint and minor erosion of the concrete edge can be seen (Appendix C: Figure C101).
- Abutment and Abutment Seat: Both abutments show substantial leakage (Appendix C: Figure C102), which is especially severe on the east side (Appendix C: Figure C103).
- Drainage System: The weep holes of the abutment were visible and seem to be operational. However one or two weep holes are below the level of the backfill and show

silt deposition within the openings (Appendix C: Figure C104). The deck has minor debris accumulation along the edges but does not hinder flow of water runoff (Appendix C: Figure C105).

3.2.4.4 Summary and Evaluation

The main source of leakage in this bridge is the backside of the abutment because abutment waterproofing details similar to Boydstown Bridge are used. The absence of waterproofing membrane makes the abutment seat and construction joint the weakest link of the system. Increase in severity of leakage on the east side indicates that the slope of the terrain surrounding the bridge has a role to play in this regard. Moreover poor design in weephole height or backfill slope has led to partial blockage of weep holes.

3.2.5 33-1011-0040-0572 Beechton Bridge

Figure 3.5: Beechton bridge

3.2.5.1 Bridge Overview

This bridge connects Beechton Road, is located over Mill Creek and was built in 2011 (Figure 3.5). The deck is skewed at 90^{o} and has no surface drains. This deck has only one span, around 31 ft. long, containing an expansion joint at one end (Appendix C: Figure C106). Due to the small span of bridge, a moment slab is used in lieu of an approach slab. Rubberized joint sealing material along with a 3/8 in. neoprene closed cell sponge is used as expansion joint material

(Appendix C: Figure C107 and C108). The abutment is a retaining wall and has no construction joints (Appendix C: Figure C109). This abutment is rehabilitated with the top half of the old abutment being removed and rebuilt (Appendix C: Figure C110 and C111).

3.2.5.2 Bridge Inspection Report

In an inspection carried out by PennDOT engineers a year after construction, minor water leakage was observed in one of the abutments (Appendix C: Figure C112). Joints were in good condition and deck drainage was good. Note: The inspection report is provided by PennDOT and was conducted on 09/06/2012.

3.2.5.3 Observations in Field Visits

Two field visits are conducted for this bridge. The following observations are made during the visits:

- Expansion Joints: There is some debris accumulation from road maintenance works. However the joints seem to be in good condition.
- Abutment and Abutment Seat: The abutment seat area is not clearly visible. However no leakage stains are visible from there. The interface of the old and new abutment sections shows severe water staining and efflorescence (Appendix C: Figure C113) and a few cracks with leakage are also visible on the new section of the abutment wall (Appendix C: Figure C114).
- Drainage System: Deck drainage seems to be operational. No weep holes are visible in the abutment.

3.2.5.4 Summary and Evaluation

The main source of leakage in this bridge is the interface of the new and old abutment. This is mostly due to differential shrinkage between the old and new concrete and may be the result of lack of a construction joint in the abutment. Efflorescence also exacerbates the problem by widening existing cracks and initiating propagation of new ones. Although waterproofing is applied to cover entire old-new concrete interface and extended to the bridge deck, the sharply angled slope of the membrane at the old-new concrete interface might be the main issue. This coupled with severe differential shrinkage may cause warping in the waterproof membrane and thus damage the membrane, voiding the protection it provides.

Implementations deviating from the standard recommendations (see PennDOT Design Manual – Part 4, May 2012: Section 14.5.6) are found at expansion joint and abutment seat. However, the short span (which implies small thermal expansion) and the 90^o skew angle (which implies negligible shear force on sealant) helps keep the joint in good condition. Since the bottom of the moment slab is lower than the abutment seat, ground water is drained away from the abutment seat with the aid of good drainage.

3.2.6 Bridge under construction: I-79 over SR 422

In addition to the five sample bridges, a visit was made to a bridge under construction. The purpose of this visit is to probe in-situ implementation of the abutment waterproofing system with a focus on the waterproofing membrane.

As shown in Appendix C: Figure C115, the backfill was completed when the field visit was made. It can be seen that a water stop is being used below the edge of the deck and is extended to the curb. It then overlaps with another piece of waterstop (Appendix C: Figure C116). The joint used in this bridge has two 1 in. polystyrene foam sheets as filler material. It can be seen that the foam sheets are loosely packed and have gaps both in between the faces of the sheets and in between adjacent sheets (Appendix C: Figure C117). Moreover it seems the waterstop is to be placed in between the deck and the approach slab, and in between the curb and the approach slab. The implementation seems to follow the recommendation and there is no sign of lapse of quality control.

3.3 VIRTUAL FIELD VISITS OF BRIDGES

In addition to the five representative bridges, "virtual" field visits by taking advantage of Google Map and inspection reports were conducted in this investigation to extend the data range so as to cover more structure types and more waterproofing details. In these "virtual" field visits, bridges of integral abutment in Pennsylvania, Massachusetts, as well as Minnesota were visited. Visits were also made for bridges containing expansion joints in Massachusetts and Minnesota. Although no inspection reports are available for Illinois and New York State, valuable information with respect to waterproofing is obtained and will be stated here.

3.3.1 Bridges with Integral Abutments in Pennsylvania

3.3.1.1 Bridge Overview

Inspection reports of two Integral abutment bridges are provided by PennDOT. The main information found in the inspection reports of these two bridges is summarized below:

- Bridge on SR0028 – 03002802800628: This bridge has a span of around 157 ft. It connects SR0028 over Cowanshannock Creek (Appendix C: Figure C118). Minor vertical shrinkage cracks are observed on the abutments. However no leakage has been found at these areas. The construction joint on the abutment is also in good condition. Note: The inspection report is provided by PennDOT and was conducted on 09/06/2012.
- Bridge on SR0536 – 16053600201980: This bridge has two spans 126 ft. long. It connects SR0536 over Redbank Creek. No issues relating to leakage are reported. Note: The inspection report is provided by PennDOT was conducted on 10/10/2012.

3.3.1.2 Summary and Evaluation

Because of the elimination of abutment seats and expansion joints, the critical aspect for waterproofing for integral abutment is construction joint and cracking. Correct implementation of waterstop is sufficient for waterproofing at construction joints. Full coverage of waterproofing membrane as required by the PennDOT design standard (Bridge Design Standard, Dwg. #667M) provides redundancy not only in construction joints, but also in cracked concrete, the latter of which is found in the first bridge.

3.3.2 Sample Bridges in Massachusetts

3.3.2.1 Bridge Overview

Inspection reports for four bridges are provided of which three bridges use integral abutments (with no joints between the deck and the approach slab) and one uses an asphaltic plug joint as expansion seal material. The year of construction for these bridges varies from 2007 to 2012. The following is the main information found in the inspection reports:

- Amherst Bridge – A0802057D-MUN-NBI: This bridge was built in 2008 and inspected on 08/04/2011. It has an integral abutment as the substructure. No leakage signs are noted or mentioned indicating that the bridge is performing well. Note: The inspection report is provided by MassDOT was conducted on 08/04/2011 (Appendix C: Figure C119).
- Bridgewater-Middleborough Bridge – B23003-92B-DOT-NBI: This bridge was built in 2007 and inspected on 07/17/2012. It has an integral abutment as the substructure. The approach sidewalk seems to have settled by approximately 1 in. Some moisture staining is observed in the same side abutment and a narrow full height vertical crack is found on the same abutment. Note: The inspection report is provided by MassDOT was conducted on 07/17/2012 (Appendix C: Figure C120).
- Hanover Bridge – H06011-B9H-DOT-NBI: This bridge was built in 2012 and inspected on 01/17/2013. It does not have an integral abutment however the type of abutment used is unknown. It uses an asphaltic plug as the expansion joint. The joints seem to have random irregularities and minor settlement. The southwest abutment shows signs of leakage. Note: The inspection report is provided by MassDOT was conducted on 01/17/2013 (Appendix C: Figure C121).
- South Hadley Bridge – S18007-AQG-DOT-NBI: This bridge was built in 2008 and inspected on 11/06/2012. It has an integral abutment as the substructure. There is no water leakage from the backwall or joints. Only water staining is found from leakage of a utility pipe. Note: The inspection report is provided by MassDOT was conducted on 11/06/2012 (Appendix C: Figure C122).

3.3.2.2 Summary and Evaluation

Good performance in waterproofing is found in the integral abutment. However, substantial stress redistribution will develop in the abutment for any movement, which generates cracking in the abutment. Without full coverage of waterproofing membrane on the abutment, water leakage will happen, as shown in Bridgewater-Middleborough Bridge.

3.3.3 Sample Bridges in Minnesota

3.3.3.1 Bridge Overview

Inspection reports for seven bridges are provided of which two bridges use integral abutments (with no joints in between the deck and the approach slab) and the rest use expansion joints. The year of construction of the bridges vary from 2006 (Built in 1975) – 2010. The following is the summary of the seven bridges' inspection reports:

- Bridge 1 (ID: 27V69): This bridge has two spans, each 76 ft. long and was built in 2007. It has a strip seal deck joint on either end. The abutment is of concrete pile footing type. The rating of the bridge is 9 for the deck, superstructure and substructure. No issues were found with any component of the bridge. There is no information on deck drainage. Note: The inspection report is provided by MnDOT and was conducted on 04/17/2013.
- Bridge 2 (ID: 27V81): This bridge has one span, 91.4 ft. long and was built in 2008. It has a strip seal deck joint on either end. The abutment is of concrete pile footing type. The rating of the bridge is 8 for the deck, superstructure and substructure. The north abutment shows signs of staining near the center barrier. The joints seem to have no problems. It seems the issue might be water staining from the backwall. There is no information on deck drainage. Note: The inspection report is provided by MnDOT and was conducted on 07/22/2013.
- Bridge 3 (ID: 10029): This bridge has two spans, totaling to 245.5 ft. long and was built in 2007. It has a strip seal deck joint on either end. The abutment is of concrete pile footing type. The rating of the bridge is 8 for the deck and substructure and, 9 for the superstructure. The joints seem to have a leak at the south and shows staining on the abutment below. There are hairline vertical cracks. However no leakage is said to

originate from these cracks. There is no information on deck drainage. Note: The inspection report is provided by MnDOT and was conducted on 05/30/2012.

- Bridge 4 (ID: 22810): This bridge has four spans, totaling to 310.5 ft. long and was built in 1975. It has two strip seal deck joints and replaces the compression seal joints previously used (replacement done in 2006). The abutment is of concrete pile footing type. The rating of the bridge is 6 for the deck, superstructure and substructure. The abutments have vertical cracks and these cracks show signs of leaching. The current strip seal joints seem to have no problems. The compression seal joints earlier seem to be failing and were causing moisture leakage on the abutment. It seems the only current issue might be water staining from the backwall. Currently for the deck drainage, both ditches (of the drainage) have standing water and slumping of slope (or slope protection). Note: The inspection reports are provided by MnDOT and were conducted on 10/06/2011 and 08/09/2005.
- Bridge 5 (ID: 49033): This bridge has one span, 100 ft. long and was built in 2010. It has concrete integral abutments. The rating of the bridge is 9 for the deck, superstructure and substructure. There are no leakage related problems reported in abutments or deck drainage. Note: The inspection report is provided by MnDOT and was conducted on 09/11/2012.
- Bridge 6 (ID: 55065): This bridge has three spans, totaling 217.7 ft. long and was built in 2007. It has a strip seal deck joint on either end. The abutment is of concrete pile footing type. The rating of the bridge is 7 for the deck and superstructure and, 8 for the substructure. Although one of the joints did have debris in it, no leakage was observed. The abutments did have minor vertical cracks. However no water staining or leakage is reported. Both the catch basins of the deck drainage are said to be in good condition at the time of inspection. Note: The inspection report is provided by MnDOT and was conducted on 09/27/2012.
- Bridge 7 (ID: 81009): This bridge has one span, 108.5 ft. long and was built in 2008. It uses concrete integral abutments. The rating of the bridge is 7 for the deck and, 9 for the superstructure and substructure. The leaching and staining is observed on all four corners of the abutments. It cannot be ascertained as to where this staining originates from. There

is no information on deck drainage Note: The inspection report is provided by MnDOT and was conducted on 08/27/2012.

3.3.3.2 Summary and Evaluation

Strip seal joint is more preferred than Compression seal joint in MnDOT practice. The better performance reported in inspection reports stems from structural advantages of Strip seal joint. Acceptable performance of abutment waterproofing is reported for both parapet and integral abutment. In MnDOT practice, the gap at the abutment is replaced with a construction joint. Thus, its abutment waterproofing details are greatly simplified, and hence are more efficient. The focus is to prevent concrete cracking due to shrinkage or differential movement. The drainage layer, being situated as high as 2/3 of the abutment height, provides good redundancy, which may be why severe leakage is not reported even though cracks are found in the abutments.

3.3.4 Information from IDOT and NYDOT

Inspection reports from Illinois and New York State are not available during the investigation. However, some critical information obtained from their inspection personnel is of great value:

1. **IDOT:** The occurrence of water leakage at joint is substantially reduced after Strip Seal Joint replaces Compression Seal Joint;
2. **NYDOT:** The occurrence of water leakage through the backwall significantly drops after the gap at the abutment seat is replaced with a construction joint.

The information, obtained from these two states, agrees well with the observations made in MnDOT reports, which is valuable for the improvement of PennDOT practice.

3.4 SUMMARY OF FIELD VISITS

Based on the observations made in the field visits, the main causes of leakage found in the five sample bridges in District 10-0 are summarized in Table. 3.1.

Table 3.1: Problems found in sample bridges

<table>
<tr><th>Bridge</th><th colspan="2">Issues in Waterproofing Details</th></tr>
<tr><td rowspan="3">Little Creek</td><td>Joint*</td><td>• Non-standard joint material
• Uneven settlement and edge damage
• Incorrect design of backup waterproofing membrane</td></tr>
<tr><td>Abutment</td><td>• Clear failure of construction joints at beam
• No indication of damage in backwall
• Inaccessible to visual inspection</td></tr>
<tr><td>Drainage</td><td>• Deck drainage impaired by uneven settlement of deck and approach slab</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td rowspan="3">Prospect #1</td><td>Joint*</td><td>• Compression joint is accessible
• Concrete edge damage
• Excessive debris accumulation due to overlay repair</td></tr>
<tr><td>Abutment</td><td>• Indication of damage in backwall but construction joint is fine
• Inaccessible to visual inspection</td></tr>
<tr><td>Drainage</td><td>• Deck drainage is impaired by debris accumulation</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td rowspan="3">Boydstown</td><td>Joint</td><td>• Compression joint is inaccessible to visual inspection
• Incorrect design of backup waterproofing membrane</td></tr>
<tr><td>Abutment*</td><td>• No waterstop and waterproofing membrane
• Inaccessible to visual inspection</td></tr>
<tr><td>Drainage</td><td>• Insufficient slop for deck drainage
• Minor clogging of weep holes</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td rowspan="3">Little Conn.</td><td>Joint</td><td>• Compression joint is accessible
• HMA edge damage</td></tr>
<tr><td>Abutment*</td><td>• No waterstop and waterproofing membrane
• Inaccessible to visual inspection</td></tr>
<tr><td>Drainage</td><td>• Minor clogging of weep holes</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td rowspan="3">Beechton</td><td>Joint</td><td>• Non-standard joint material</td></tr>
<tr><td>Abutment*</td><td>• Cracking due to differential shrinkage
• No construction joint
• Sharp angle of waterproofing membrane at old-new concrete abutment interface</td></tr>
<tr><td>Drainage</td><td>• No issues found</td></tr>
</table>

Note: ***** indicates main cause of leakage in bridge

The severe water leakages found in all the sample bridges indicate that there are fundamental inadequacies in the typical waterproofing details implemented in them. In addition to bad quality control, the inadequacy stems from flaws induced by: 1) Insufficient design; 2) Improper implementation and 3) Lack of robustness. The inaccessibility to visual inspection obstructs the close monitoring on the damage initiation from the flaws. Therefore, detailed analysis of the typical waterproofing details is being carried out and will be reported to PennDOT in the next report.

Based on observations made from the "virtual" field visits, a substantial improvement can be seen in bridges with integral abutment in PennDOT, MassDOT and MnDOT. This indicates that eliminating the gap at the abutment seat, which is common in the sample bridges, will greatly enhance the effectiveness of abutment waterproofing for parapet abutments. This postulate is further supported by MnDOT inspection reports, as well as information based on NYDOT practice. The replacement of Compression seal joint with Strip seal joint also demonstrates a significant increase in waterproofing capacity, which is documented in MnDOT inspection reports and IDOT practice.

These observations from the real and "virtual" visits shed light on the analysis of expansion joints and abutment waterproofing, and thus provide much-needed insights for improvement in future practice.

3.5 ANALYTICAL RESEARCH

The following research is conducted on the components of the bridge waterproofing:

- Finite element analysis of parapet abutment waterproofing membrane
- Finite element analysis of differential shrinkage at old-new concrete interface
- Finite element analysis of effect of skew angle on compression seal joint
- Finite element analysis of traffic loading on the steel extrusion of a strip seal joint
- Experimental analysis of elongation of strip seal

3.5.1 Finite element analysis of parapet abutment waterproofing membrane

A typical waterproofing membrane used in PennDOT for abutment is illustrated in Figure 3.6. The adhesive layer in the waterproofing membrane is used to glue it on concrete surface, thus forms an interfacial layer between membrane and concrete. Based on ASTM manual and information from suppliers, the bond strength of waterproofing membrane is generally about less than 145 psi and the fracture energy to delaminate the interface is about 8.6 lb/in. based on its peel-off strength.

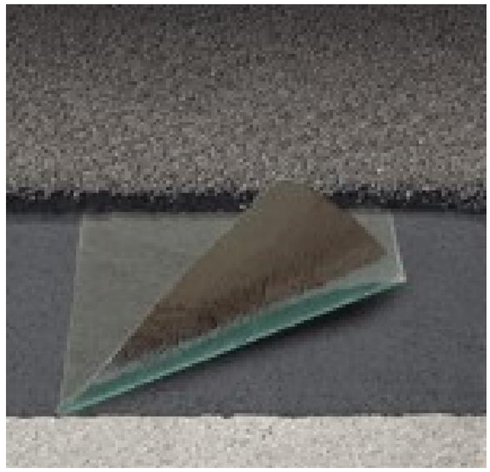


Figure 3.6: Polymer modified asphalt waterproofing membrane with adhesive

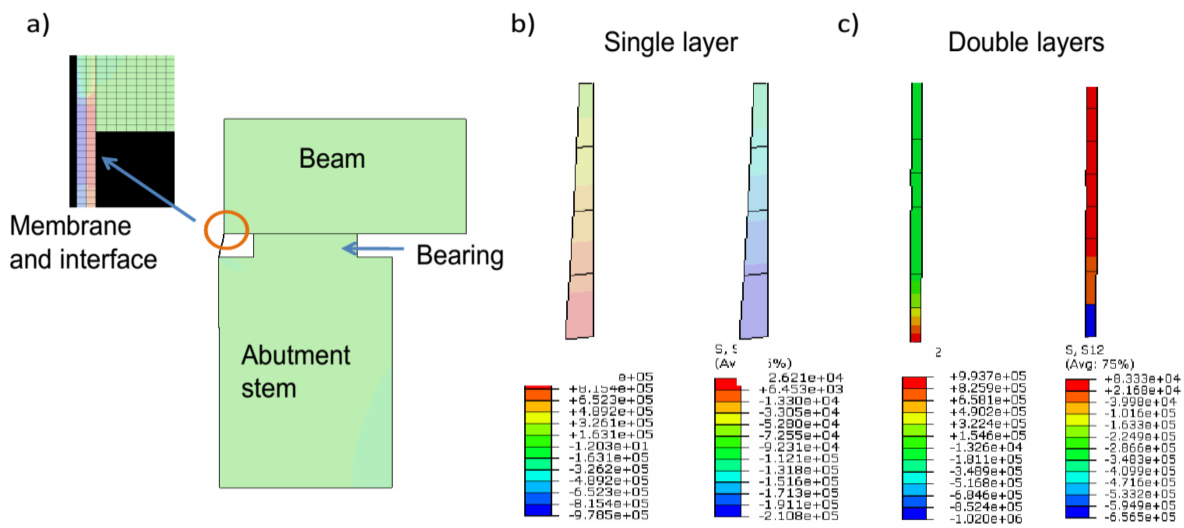


Figure 3.7: ABAQUS model of membrane peeling off

To investigate the strength distribution in the adhesive interface between concrete and waterproofing membrane, a computational model is built by using Abaqus (Figure 3.7a). In the model, the interface between membrane and concrete is typical in PennDOT practice: 12 in. long on abutment stem side, and 12 in. long on deck side. Considering the movement limit allowed for expansion joints, a horizontal displacement equal to 0.6 in. will be applied to the deck. This displacement is equivalent to a 100 ft. long bridge undergoing a temperature variation equal to 104^{o}F, which is common in Pittsburgh area; see average monthly weather given in Table 2.1 in Chapter 2. Since there is no concrete information on the modulus of elasticity of the membrane or on the strength of the adhesive used, these values are estimated based on the tensile strength requirement from PennDOT and the testing procedure of the membrane. The adhesive is assumed to be stronger than the membrane.

In figures 3.7b and 3.7c, the stress distribution along the membrane-concrete interface is plotted when a contraction equal to 0.6 in. happens in the deck in winter. From the plots, it can be seen that severe stress concentration exists in the interface adjacent to the two concrete corners. This stress concentration is caused by the *material mismatch* and *geometry irregularity* and can be explained by nonlinear fracture mechanics, which is beyond the scope of this investigation although widely studied in fiber composite materials for metal-composite hybrid joint.

3.5.2 Finite element analysis of differential shrinkage at old-new concrete interface

For projects where the abutment is rehabilitated, property and age of the concrete on the opposing sides of the old-new concrete interface differ significantly. Substantial shrinkage in the young concrete will lead to cracking at the interface, and thus cause water leakage. This is evident in the Boydstown Bridge and Beechton Bridge, even though the latter one had a waterproofing membrane applied at the interface.

A finite element analysis was carried out using Abaqus. The American Concrete Institute shrinkage model is used. The Beechton bridge abutment is used as the sample abutment. The analysis simulates stresses at the old-new concrete interface at the end of 365 days. The stresses are shown in figure 3.8. It can be seen that tensile stresses in the new concrete almost reach 740 psi (5.084 MPa) which is higher than the tensile strength of concrete. These stresses are possibly what contribute to the cracks in the abutment wall.

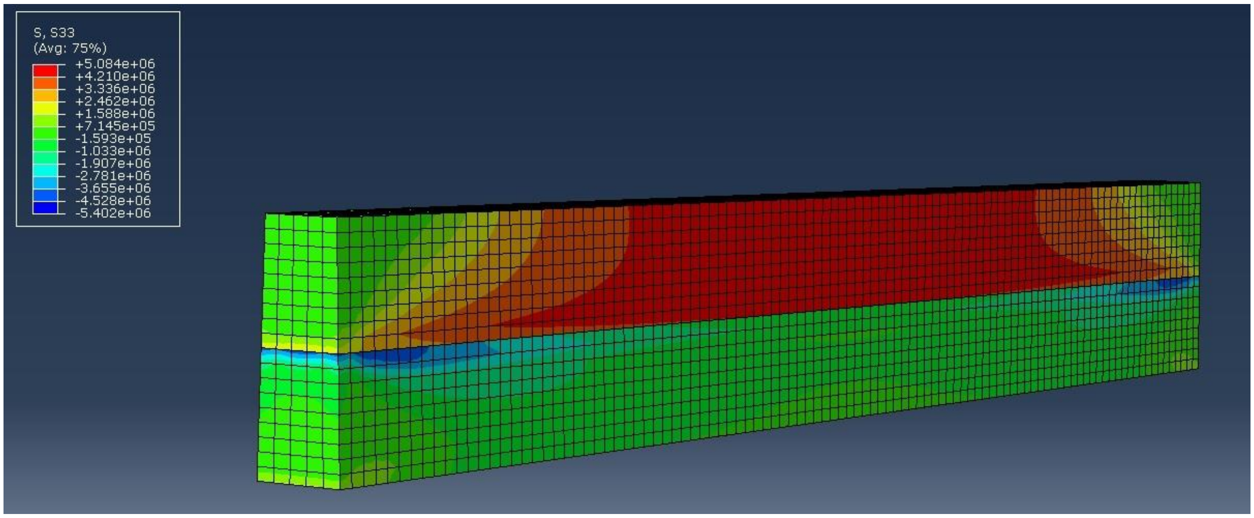


Figure 3.8: Stress distribution in rehabilitated abutment

3.5.3 Finite element analysis of effect of skew angle on compression seal joint

In current PennDOT practice, there is no limit for the skew angle when Compression Seal Joint is used. It is not known how the skew angle affects shear stresses experienced by the compression seal in the joint.

To comprehensively simulate this, 3D computational models are built in Atena. In the models, three skew angles, i.e. 0, 20, and 45 degrees, are used; see Figure 3.9. Normal concrete having a Young's modulus of 4351 ksi and Poisson's ratio of 0.2 is used for the concrete deck. As for neoprene seal, its Young's modulus is taken as 2001 psi and Poisson's ratio as 0.01 (Kinloch, Lau, & Williams, 1994). At the contact surface, a constitutive relation similar to Mohr-Coulomb model is used, characterized by cohesion strength of 145 psi (to simulate the strength of lubricant-adhesive) and frictional coefficient of 0.2 (to simulate the friction between neoprene seal and concrete surface).

When an expansion of 0.4 in. is applied to the concrete deck, the stress on the contact surface is investigated for different skew angles. Here 0.4 in. is selected in that it is equivalent to a 100 ft. long concrete slab undergoing a temperature variation equal to 86^{o}F, which is most common for bridges in Pennsylvania. Under this deformation, stress development on the contact surface will be different for different skew angles.

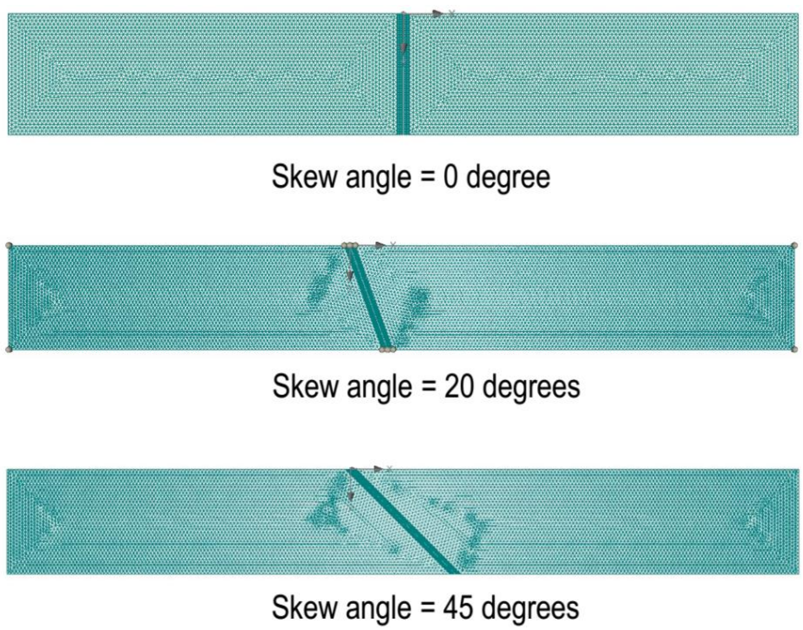


Figure 3.9: Effect of skew angle on the contact surface

For all the skew angles, there is only normal stress on the contact surface before thermal deformation. However, as the thermal deformation grows, significant shear stress is developed on the contact surface for non-zero skew angle. For example, at the end of the expansion, the shear stress for a skew angle of 20 degrees is 75 psi, over half of the cohesion strength; and for a skew angle of 45 degrees, it is 139 psi, almost reaching the assumed cohesion strength. Note that traffic loading in accordance to AASHTO specification (AASHTO, 2010) is considered in the simulations, although its effect on contact stress is found to be negligible.

3.5.4 Finite element analysis of traffic loading on the steel extrusion of a strip seal joint

To investigate the strength of the anchorage of the extrusion, 3D computational models are built in Atena. In this investigation, both extrusions with and without armor are simulated, although armor is not preferred in current PennDOT practice due to the issues of air pockets and cracking in concrete underneath the armor. Figure 3.10a shows a joint of armor under traffic load. In Figure 3.10b, a joint without armor is studied under same traffic load. The stress distribution in the anchorage stud, steel extrusion and concrete block-out is obtained when a truck is driving through and is considered in accordance to AASHTO specifications (AASHTO, 2010).

From the stress distribution obtained, it can be seen the maximum stress in the anchorage stud is about 2118 psi, far less than the yield strength and fatigue strength of steel. The maximum stress in the steel extrusion is only 1336 psi, demonstrating a substantial safety margin. The maximum tensile stress in the concrete block-out is about 163 psi, only around 35 percent of its tensile strength. Therefore, there will be no macro-cracking around the anchorage stud (micro-cracking due to shrinkage may exist but it will not significantly affect the pullout strength).

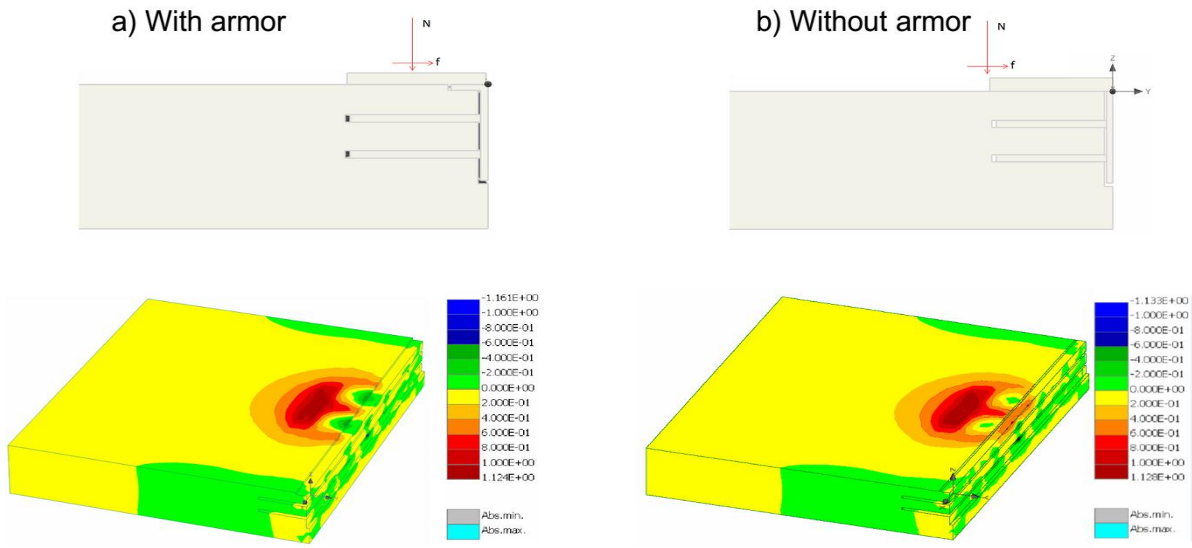


Figure 3.10: Analysis of Strip seal joint in Atena

In current PennDOT practice, 5/8’’ x 10’’ stud is generally used as the anchorage member. For concrete without cracks, block-out with strength = 4000 psi (strength of Class AAA-P), its pullout strength is about 16000 lb. according to ACI design code (American Concrete Institute Committee 318, 2011). This is significantly greater than the force obtained in the push-out test for strip seal, which is only about 2700 lb. This means the anchorage of extrusion has a larger safety margin than the strip seal, and thus enables the extrusion to hold the strip seal safely even when significant load is imposed on the strip seal.

3.5.5 Experimental analysis of elongation of strip seal

To investigate the strength of strip seal so as to evaluate the safety margin of the Strip Seal Joint system, a seal push-out test similar to that on a Modular Bridge Expansion Joint (MBEJ) is conducted. A sample of Strip Seal Joint provided by D.S Brown, a supplier approved by PennDOT. This sample is tested by the research team. As shown in Figure 3.11, the sample is 3 ft. long and lubricant-adhesive is used during installing the strip seal into the steel extrusions. To prevent the rotation of steel extrusions during push-out test, steel bolts procured from McMaster are used to fix the steel extrusions.

Figure 3.11: Strip seal joint fixture used in experiment

The test is conducted on a loading machine by pushing a one-foot long steel rod into the strip seal (Figure 3.12). In the test, the strip seal exhibits strong resistance to the push-out. To avoid the loading piston from touching the steel extrusion, the test is stopped after the load reaches 2700 lb. Under this load, the strip seal does not fail; neither is there a sign of push-out of strip seal from the extrusions (Figure 3.13). Considering that the AASHTO requirement (AASHTO, 2010) for MBEJ is 1600 lb., the strip seal strength is significantly higher, and thus provides sufficient safety margin to the Strip Seal Joint.

In addition, the strip seal displays excellent ductility in the test. When the load reaches 2700 lb., the strip seal undergoes a deformation over 4 in. deep without damage. This shows that the strip seal has a high tolerance to debris accumulation. This is a great advantage compared to

Compression Seal Joint, which cannot sustain large vertical deformation and is thus sensitive to debris accumulation.

Figure 3.12: Loading of strip seal

Figure 3.13: Around 4 in. deflection at the end of loading

4.0 CONCLUSIONS AND PRELIMINARY RECOMMENDATIONS

4.1 INTRODUCTION

Analysis of current design and construction recommendations, observations of in-situ implementation and performance of waterproofing details show that there exists striking inadequacy in current waterproofing details implemented in PennDOT practice, especially for bridges of parapet abutments. This inadequacy is evidenced by severe water leakage found in all 5 bridges visited in Pennsylvania, all of which were built as per PennDOT recommendations after 2008 and were found to have severe water leakage at a much earlier age than expected by design.

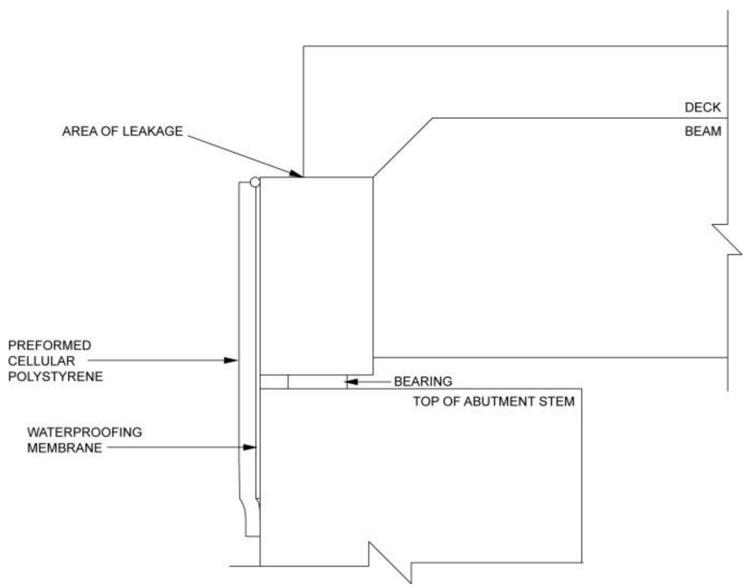


Figure 4.1: Implementation of Waterproofing

Dysfunction or damage in any of the 3 primary subsystems: expansion joints, abutment waterproofing or drainage, affect the effectiveness of the entire waterproofing system and lead to water leakage on the substructure. For example, failures in expansion joints or abutment waterproofing can result in water leakage through the gap at the abutment seat, and thus accelerate corrosion, cracking and degradation of bearings, abutment and other important structural members. This accelerated deterioration due to water leakage is highly evident in the field visits in Pennsylvania; (see Chapter 3).

Figure 4.2: Gaps in preformed polystyrene

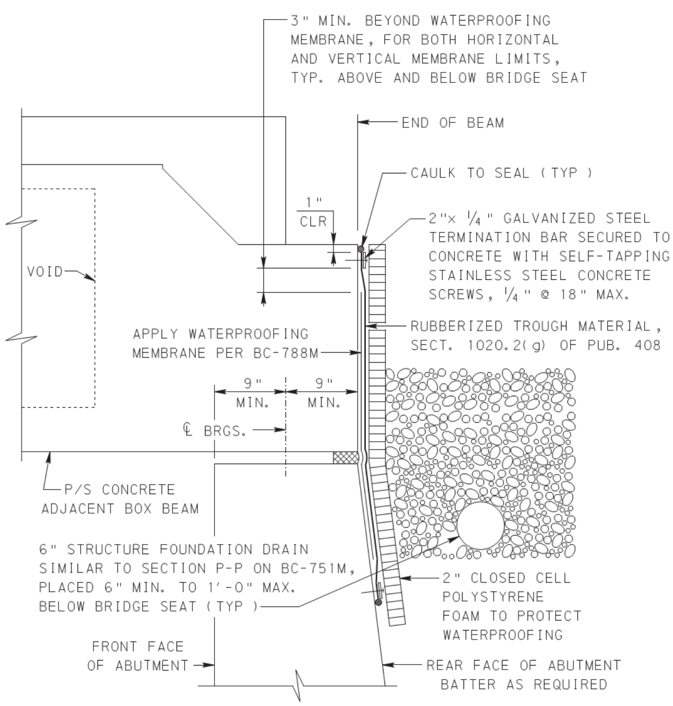


Figure 4.3: Typical representative waterproofing detail for parapet abutment

Figure 4.4: Cracking and erosion of joint edges

Based on findings detailed in previous chapters, the inadequacy in current waterproofing practice in PennDOT may stem from 2 primary sources: 1) insufficient design of key structural components in the subsystems; and 2) lack of redundancy in sub-level and global level systems. The former one causes the damage of waterproofing members in service at an unexpectedly young age, e.g., the dislocation or laceration of waterproofing membrane of the abutment by sharp coarse stones in the backfill (Fig. 4.2) and, damage of the joint edge by impact forces caused by traffic and snowplow (Fig. 4.3). The latter changes the system into a series-coupled chain, with its capacity being dictated by the weakest link. Additionally, poor design of the waterproofing membrane does not provide any redundancy to the expansion joint, thereby substantially reducing the robustness of the expansion joint (Fig. 4.1 and 4.4).

Another obstacle challenging the current progress towards a better waterproofing practice is the unavailability of advanced tools in routine inspections, which heavily relies on visual observation. These challenges are documented in PennDOT inspection reports, none of which identify the exact source of leakage or location of damage in the backwall of abutment, although it is almost ascertained that the water leakage is caused by failure in abutment waterproofing.

Without knowing the failure location and its mechanism, any evaluation of abutment waterproofing details would be inconclusive.

4.2 EVALUATION OF ABUTMENT WATERPROOFING DETAILS

The primary goal of the abutment waterproofing is to prevent water from penetrating through the abutment. Currently, two types of abutment systems are used in bridge construction in PennDOT practice: 1) parapet abutment; and 2) integral abutment. Because of the very dissimilar structural style and application limits, the corresponding abutment waterproofing details applied are very different. Therefore, separate evaluation and recommendation are needed.

4.2.1 Parapet Abutment

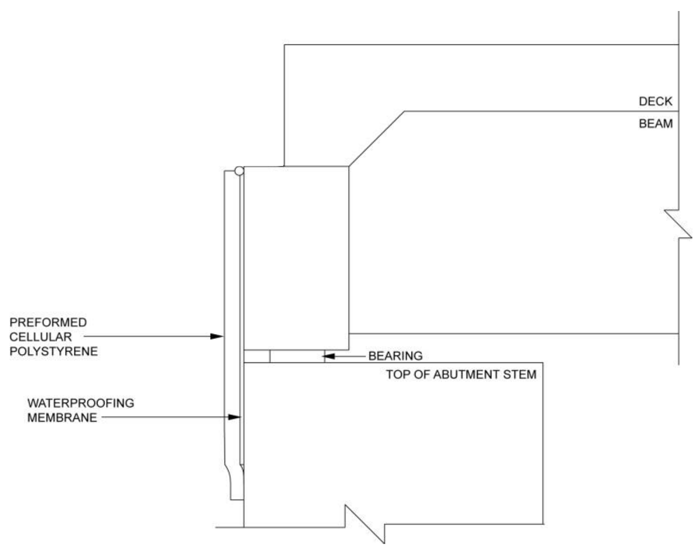


Figure 4.5: Waterproofing details similar to Little Creek Bridge

Structurally, a parapet abutment is not rigidly connected to the superstructure. This allows the deck and girder to move when temperature variation causes thermal expansion in deck, which is significant in longitudinal direction. With the help of bearings, which work like rollers, only vertical (no horizontal) load is transmitted from the superstructure to the abutment. Due to its advantages in structural simplicity, construction efficiency and application range (applicable for both short- and long-span bridges), parapet abutment is popular in current practice and most of the bridges in Pennsylvania are constructed using parapet abutments. For example, all the five sample bridges investigated in Chapter 3 are using parapet abutments.

Based on the design manuals and field visits, typical abutment waterproofing details in parapet abutment implemented in construction are illustrated in Fig. 4.5 and Fig. 4.6. For example, waterproofing details similar to Fig. 4.5 are used in the Little Creek Bridge, where the end of approach slab sits on the beam; while those similar to Fig. 4.6 are implemented in the Boydstown Bridge, where the end of approach slab sits on the abutment or ground. As demonstrated in these figures, the critical location of parapet abutment is the through-thickness gap at the abutment seat. In addition, the construction joint and old-new concrete interface in the rehabilitated abutment is also susceptible to water leakage.

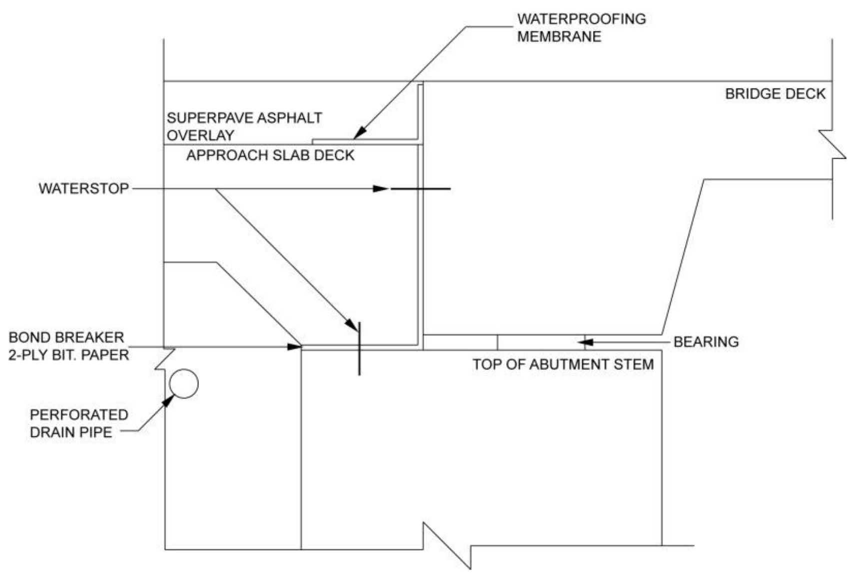


Figure 4.6: Waterproofing details similar to Boydstown Bridge

To protect these key areas, the central components of abutment waterproofing are the waterproofing membrane, polystyrene cover (or other types of foam protection), and waterstop. The waterproofing membrane is used to prevent water from penetrating through the gap at the abutment seat, as well as waterproofing backup for joints. The purpose of the polystyrene cover is to protect the waterproofing membrane against damage by the backfill, which contains sharp coarse material. A waterstop is installed in the construction joint to lessen the water pressure in case of water ingress. Note that for parapet abutment, it is not required by current PennDOT recommendations to cover the construction joint with waterproofing membrane.

4.2.1.1 Gap at Abutment Seat

The gap at abutment seat (Fig. 4.5 and Fig. 4.6) is critical for waterproofing because it is a through-thickness channel that water can directly flow through. To prevent water from flowing inside the abutment seat, waterproofing membrane has to be used, typically being glued on the abutment stem (which is fixed) at one end and on the deck (which is allowed to move longitudinally under temperature variation) at the other end; see Fig. 4.7. Therefore, its bond strength to resist peeling off from concrete is of paramount importance.

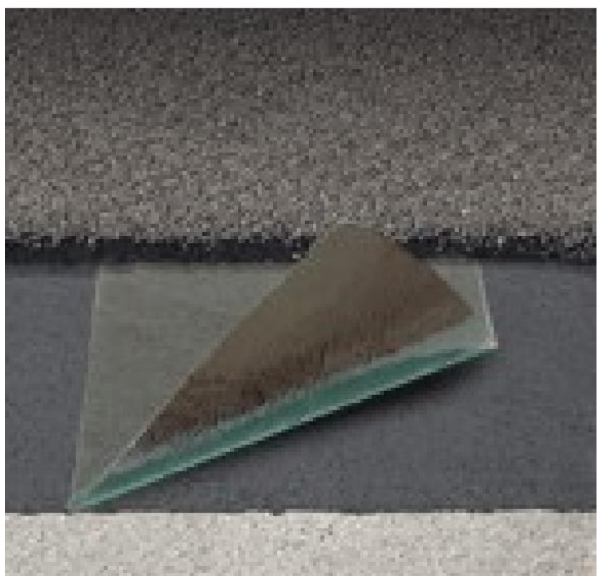


Figure 4.7: Polymer modified asphalt waterproofing membrane with adhesive

A typical waterproofing membrane used in PennDOT for abutment is illustrated in Fig 4.7. The adhesive layer in the waterproofing membrane is used to glue it on concrete surface, thus forms an interfacial layer between membrane and concrete.

Based on the numerical studies, it is found there is a generic flaw existing for the waterproofing membrane at the gap of abutment seat: the membrane will be peeled off due to stress concentration. The delamination cannot be eliminated by adding protection on membrane because it has nothing to do with the scratch or laceration induced by backfill. Neither can it be mitigated by using an additional layer of membrane. This delamination is due to stress concentration induced by the special geometry at the abutment seat. The friction caused by backfill, which is not considered in the model, will further exacerbate the interfacial damage because it constrains the movement of membrane.

Besides concerns of delamination, redundancy is another issue. The interface delamination initiates at the corners of the abutment seat, thus undermining the protection afforded by the polystyrene cover. So, the only redundancy available after membrane delamination is residing on the abutment drainage system. Efficiently discharging water from the abutment seat will substantially lower the severity of water leakage through the delaminated interface.

To mitigate the interface delamination and to improve redundancy in waterproofing details at the abutment seat as shown in Fig. 16, the following approaches may be adopted:

1. To extend the membrane-concrete interface to ensure no peeling off from the deck end;
2. Avoid overlapping the membrane to form a double-layer;
3. Using softer membrane with stronger adhesive to mitigate the stress concentration;
4. To reserve extra waterproofing membrane between the abutment seat and deck so as to accommodate deck movement;
5. To add drainage layer to discharge water away from the abutment seat;

However, this means more demands in cost, skill and quality control. One thing that needs to be mentioned is that, it is difficult to evaluate the effectiveness of these approaches in mitigating interface delamination because the abutment seat is inaccessible for visual inspection. Therefore, technical tools of water leakage detection need to be supplemented.

4.2.1.2 Construction Joints in Abutment

In addition to the abutment seat, attention is required on construction joints. Typical waterproofing details for construction joints in abutment are illustrated in Fig. 4.8, where waterstop is the only waterproofing component. According to the structural design, little force is transmitted through the construction joint. Therefore, safety margin is not the main concern for waterstop used in construction joint. Instead, water leakage is primarily caused by cracks and delamination between waterstop and concrete.

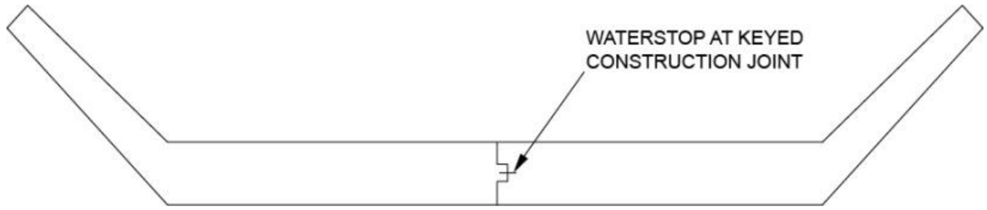


Figure 4.8: Typical implementation of construction joint

To eliminate the cracking and delamination, it is important to 1) improve the bond between waterstop and concrete; and 2) control the shrinkage of concrete. Currently, PVC waterstops are widely used in PennDOT practice. Although its overall performance is acceptable when correctly implemented, the adhesion between PVC waterstop and concrete is not strong. A study (Kryton, Retrieved 2013) found that crystalline waterstop has a good bond with concrete and thus shows better performance.

As for controlling concrete shrinkage, it is still an intensively studied topic, and is thus out of the scope of this investigation. However, since shrinkage cracking mostly happens when concrete is young, correct construction implementation will help strengthen the concrete to resist cracking in the waterstop-concrete interface. Proper implementation practices include:

- Selecting low shrinkage mix design;
- Curing concrete until its strength has fully developed;
- Ensuring there are no irregular deformations, e.g., warping, in the waterstop area while casting concrete.

Although current waterproofing details at construction joints have been found to perform well in field visits, the redundancy is low because dysfunction of the waterstop leads to failure of the whole system. To avoid this type of weakest link, adding redundancy is necessary. This can be achieved by adding a waterproofing membrane along the construction joint (along with preformed cellular polystyrene).

4.2.1.3 Old-new Concrete Interface

For project where the abutment is rehabilitated, property and age of the concrete on the opposing sides of the old-new concrete interface differ significantly. Substantial shrinkage in the young concrete will lead to cracking at the interface, and thus cause water leakage. This is evidenced in the Boydstown Bridge and Beechton Bridge, even for the latter one, a waterproofing membrane was applied at the interface.

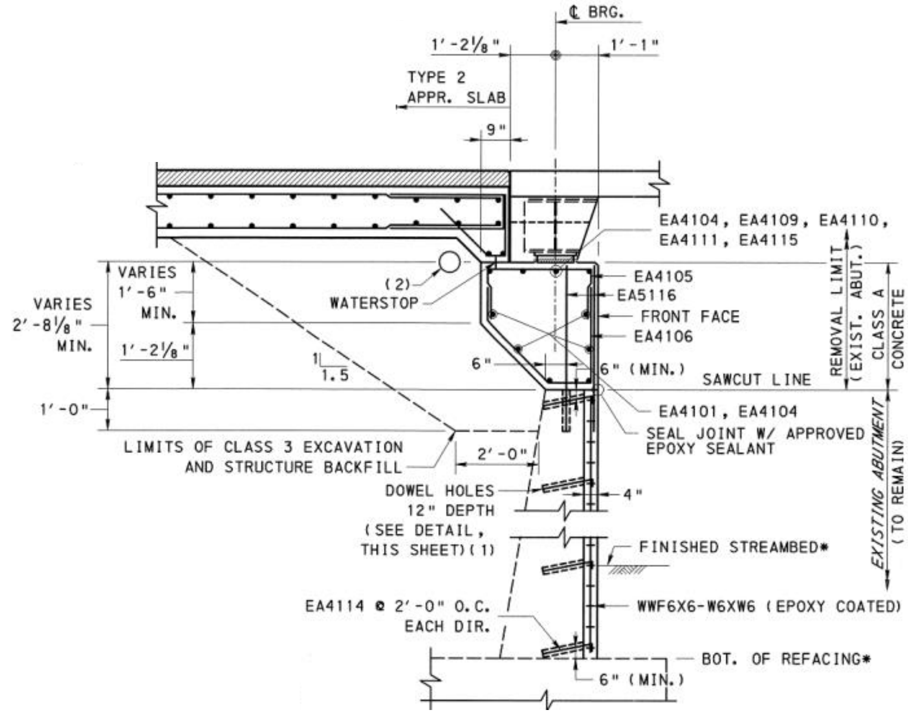


Figure 4.9: Boydstown Bridge old-new concrete interface details

The details at the old-new concrete interface for the Boydstown Bridge and Beechton Bridge are shown in Fig. 4.9 and Fig. 4.10 respectively. It can be found that waterstop is not used, at the interface, in these two bridges. Considering the fact that severe water leakage is found at the old-new concrete interface, a conclusion can be drawn that waterstops may be indispensable for rehabilitated abutments. Similarly, enhancing the robustness of the rehabilitated abutment can be done by adding a waterproofing membrane and drainage layer at the interface.

Note that substantial differential shrinkage may cause cracking in locations other than the old-new concrete interface. Preventing water from seeping from these cracks is beyond the scope of this report as it is more related to structural analysis and design of the abutment based on stress redistribution caused by shrinkage. However, during implementation, selecting low shrinkage concrete and good curing practices will mitigate shrinkage-induced stress in the abutment, and thus reduce the risk of concrete cracking.

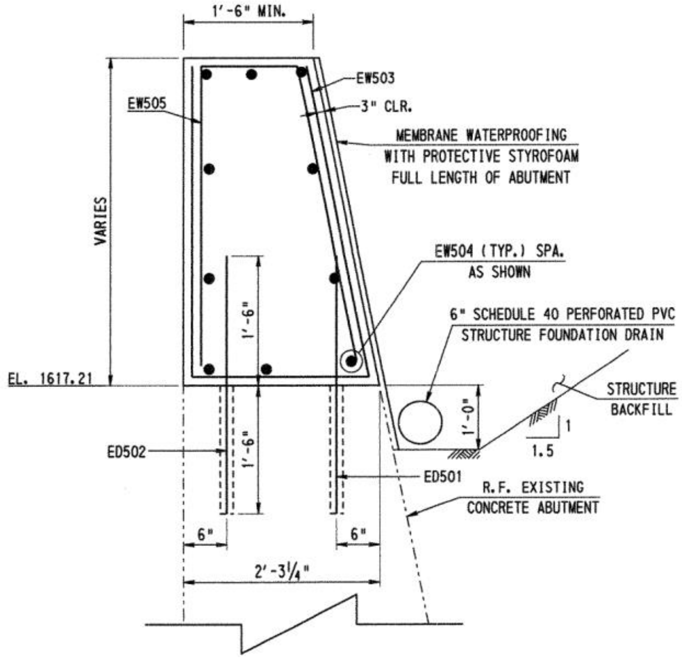


Figure 4.10: Beechton Bridge old-new concrete interface details

4.2.1.4 Integral Abutment

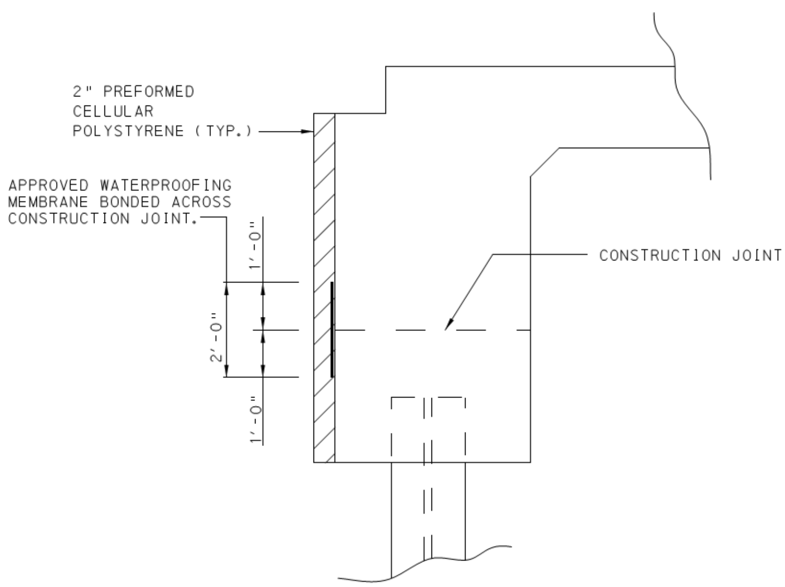


Figure 4.11: Integral Abutment waterproofing

Integral abutments (Fig. 4.11) usually do not have issues of leakage due to the absence of expansion joints and lack of an abutment seat. The only problem that could cause water leakage is shrinkage cracks or stress redistribution on the abutment stem. However due to its size (small) and the implemented protection (waterproofing membrane is applied to whole abutment or to key locations like construction joints), the risk of water leakage through the abutment is slim. As documented by the “virtual” field visits in Chapter 3, integral abutments following PennDOT, MnDOT and MassDOT practices have not shown any issues of leakage.

4.2.2 Abutment-Wingwall Interface

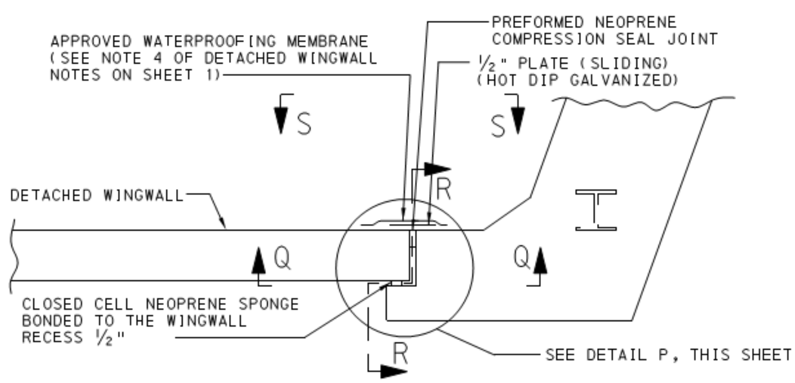


Figure 4.12: Implementation of Abutment-Wingwall Interface

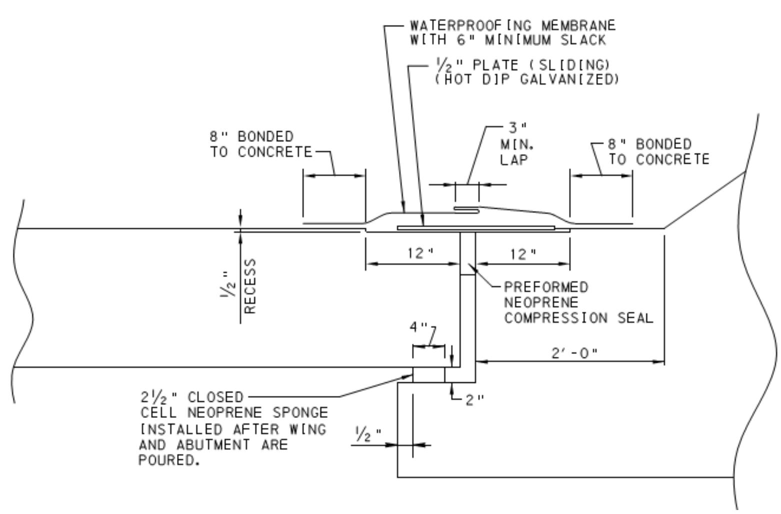


Figure 4.13: Detail P in Fig. 24

The abutment-wingwall interface is not critical to structure performance but is important for the longevity of the structure as a whole. While the interface of parapet abutment does not have any information on the joint used here, the interface of integral abutment uses an expansion joint at this interface utilizing a preformed neoprene compression seal along with a waterproofing membrane and a sliding plate; See Fig. 4.12 and Fig. 4.13. For normal abutment (less than 30 ft.), the thermal expansion is small at this location. Therefore, compression seal and waterstop may be adequate. To raise the redundancy, waterproofing membrane or drainage layer can be added.

4.2.3 Summary of Abutment Waterproofing

Based on the preceding analysis, the following evaluation may be obtained for abutment waterproofing details:

1) **Parapet Abutment:**
    - A weak spot will exist if there is a through-thickness gap at the abutment seat. The waterproofing membrane covering this gap will experience severe stress concentration during cyclic thermal expansion. To reduce the risk of membrane peeling off, approaches of high demands in cost, skill and quality control have to be adopted. Furthermore, the diagnosis and prognosis of this weak spot is difficult because it is inaccessible to visual inspection. Therefore, the best remedy to this generic flaw is to eliminate the through-thickness gap (for example, using integral abutment). Practice in MnDOT and NYDOT shows that if the through-thickness gap is replaced with a construction joint by changing the abutment geometry, the risk of water leakage from the backside of abutment is significantly reduced. However, adding a backwall eliminate the possibility to place joints away from the bridge deck.
    - A waterstop and correct design implementation are critical for the performance of waterproofing details at construction joint. Its redundancy can be strengthened by adding a waterproofing membrane and drainage layer.
    - Shrinkage is a major concern for rehabilitated abutment because of the shrinkage crack at the old-new concrete interface. A Waterstop is needed at the interface to

inhibit leakage at these cracks. To further improve the robustness, addition of waterproofing membrane and drainage layer should be considered.

2) Integral Abutment:

- Construction joint is the only possible channel for water penetration other than bad quality control in construction. The waterproofing membrane is the only point of protection in the integral abutment
- Stress redistribution induced by shrinkage or thermal expansion will generate cracks in the abutment. The cracking location cannot be determined a priori because the stress redistribution is complicated. To enhance the redundancy to resist concrete cracking, full coverage of waterproofing membrane is necessary.

Based on these evaluations, enhancement in abutment waterproofing will be proposed in the executable recommendations later in the chapter.

4.3 EVALUATION OF EXPANSION JOINTS

Compression seal joints and strip seal joints are generally not designed to carry any traffic load and are used for accommodating small and moderate expansions (< 5 in.); while steel finger joints and MBEJs are designed to carry traffic load and are designed for large expansions (> 5 in.). Since structural analysis has to be used to design Steel Finger Joint and MBEJ and experimental protocol is given by AASHTO for MBEJ, their safety margin is usually acceptable.

However, there is no structural analysis used for design of Compression Seal Joint and Strip Seal Joint. Their safety margin is vague. Especially, Compression Seal Joint is found to perform poorly in the field visits and inspection reports, seal spalling and damage being evident in several bridges. Therefore focus of this investigation is on Compression Seal Joint and Strip Seal Joint. Because their working mechanism and constituent parts are totally different, separate analyses are carried out here.

4.3.1 Compression Seal Joint

The compression Seal Joint is popular in PennDOT practice because of its advantages in construction efficiency and cost. A typical Compression Seal Joint in PennDOT is illustrated in Fig. 4.14, among the constituent parts listed in Chapter 2, the critical component in the Compression Seal Joint is the neoprene seal. It is held in place by mobilizing friction against adjacent vertical joint faces. Thus, the neoprene seal is always in a state of compression. Obviously, the performance of the Compression Seal Joint is directly related to its contact with the joint faces, which is influenced by skew angle and integrity of joint edges.

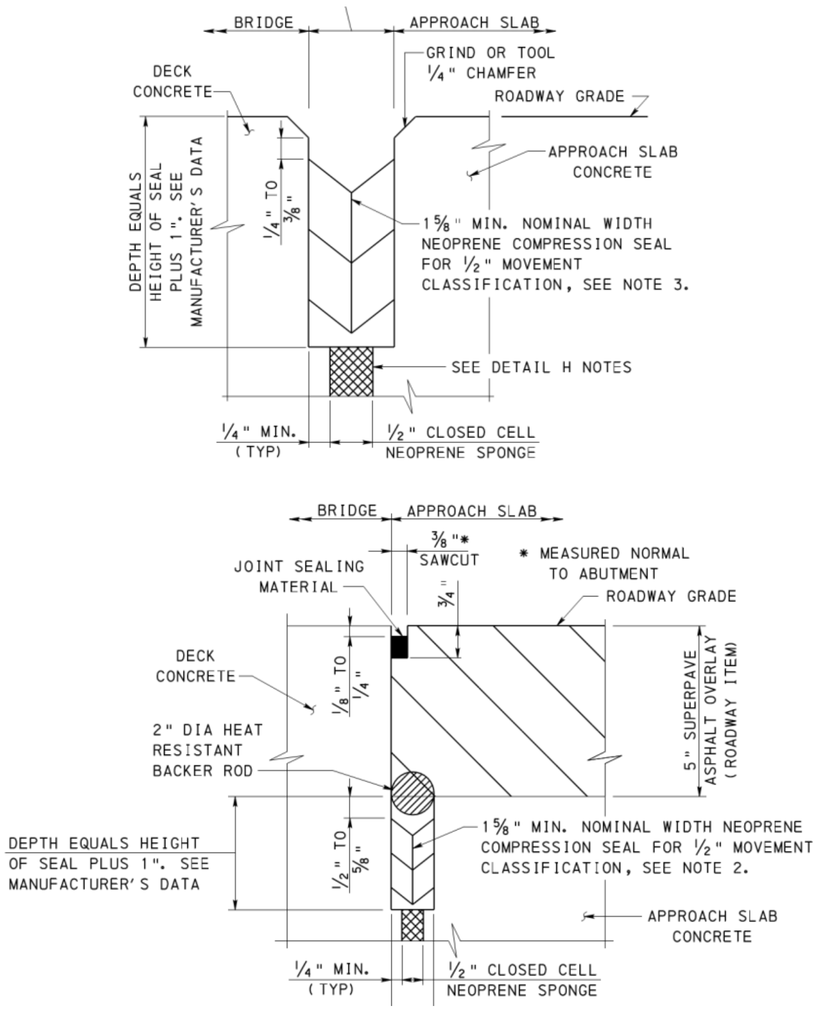


Figure 4.14: Compression seal in joint without (above) and with asphalt overlay (below)

4.3.1.1 Skew Angle Effect

In current PennDOT practice, there is no limit for the skew angle when Compression Seal Joint is used. For example, the bridges visited in Pennsylvania have skew angles ranging from zero to 45 degrees; while in Ohio, the skew angle is limited to 15 degrees. In the field visits, it is found that if the deck span is short (e.g., less than 40 ft.) and allowed movement is small (e.g., less than 0.5 in.), the Compression Seal Joint seems to be in good condition even there is big skew angle. For example, joints in Boydstown Bridge, Beechton Bridge and Connoquenessing Bridge are all working functionally as expected. However, if the deck span is long (e.g., longer than 100 ft.) and the allowed movement is moderate (e.g., greater than 1.5 in.), the performance of the Compression Seal Joint is poor. For instance, in Prospect #1 Bridge, the joint is the main cause of the water leakage.

It is well known that if shear stress is over the cohesion strength, the neoprene seal will move and slip between seal and concrete surface will happen. As a result, the integrity of the joint will be compromised. The computational models verify that increasing the skew angle can dramatically reduce the safety margin of the Compression Seal Joint. Therefore, skew angle must be limited for a Compression Seal Joint.

4.3.1.2 Edge Protection

In addition to skew angle, the condition of joint edge is important for the Compression Seal Joint. If the edges are chipped off, the contact between neoprene seal and concrete will be damaged. Furthermore, the damaged edge will expose the Compression Seal Joint to traffic load if it is installed on the top. This makes the joint vulnerable because Compression Seal Joint is not designed to carry significant load. Of course, this can be avoided by installing the Compression Seal Joint at the bottom. However, it will deny the access to visual inspection and increase cost in repair.

In the field visits, it is found that in practice it is popular to use concrete surfaced bridge deck on one side and hot-mix asphalt (HMA) surfaced approach slab on the other side. The material dissimilarity on the opposing sides of the joint will lead to uneven settlement, which is conspicuous in the Little Creek Bridge (see Chapter 3). This uneven settlement will expose the extruding edge to traffic load and snowplow, and thus cause damage and cracking. In addition, it will disturb the water runoff on the deck and result in water accumulation sitting on the joint.

Therefore, to ensure the functionality of the Compression Seal Joint, the joint edge must be strengthened. This may be done by using stronger concrete block-out and steel armor, although the latter has problems caused by shrinkage and air bubbling between the concrete and steel surface.

4.3.2 Strip Seal Joint

Instead of contact friction by compression, Strip Seal Joint is using steel extrusion anchored inside the concrete block-out to hold the strip seal. A typical Strip Seal Joint in PennDOT practice is illustrated in Fig. 4.15. For a Strip Seal Joint, the critical components include steel extrusion, anchorage studs and strip seal. Based on its working mechanism, the performance of the Strip Seal Joint is directly related to the strength of strip seal, anchorage of extrusion and integrity of joint edges.

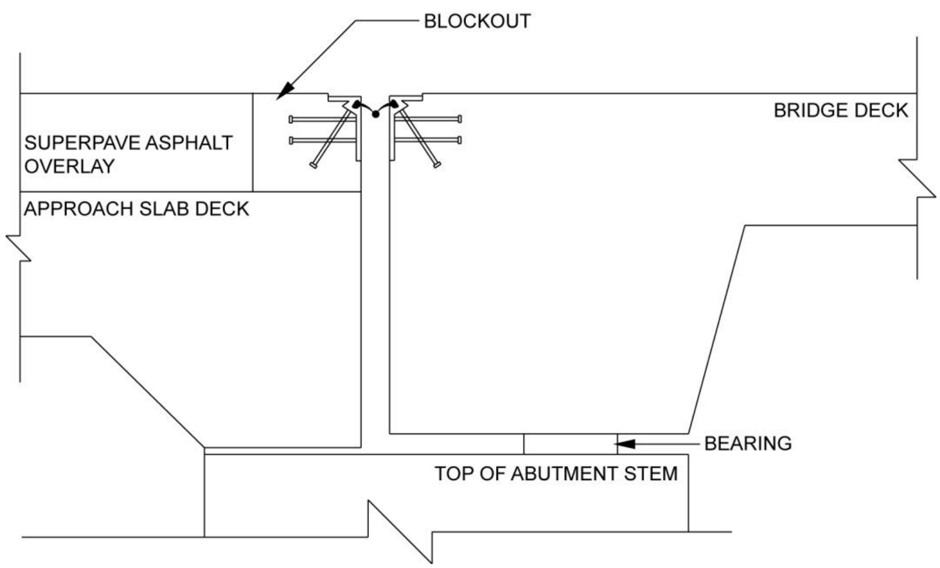


Figure 4.15: Typical strip seal joint implementation

4.3.2.1 Strength of Strip Seal

In current AASHTO and PennDOT recommendations, Strip Seal Joints are not designed to carry significant load. There is no structural analysis employed for the strip seal nor is there any experimental protocol for testing of the strength of strip seals. While in service, the Strip Seal

Joint may have to carry traffic load if severe debris accumulation happens. For example, in Prospect #1 Bridge, pavement maintenance introduced a significant amount of debris on the deck after repair.

The tests conducted to simulate debris accumulation showed that the strip seal could deform substantially under traffic loading well beyond the design requirement. However, it should be noted that this while this is good performance, this debris should not be allowed to remain in the strip seal and should be cleaned out as soon as possible, because the long term effect of debris accumulation has not been researched and is not how the seal is designed to work.

4.3.2.2 Anchorage of Extrusion

The steel extrusion, which holds the strip seal, is anchored in the concrete block-out, typically by steel studs (Fig. 4.15). If the anchors/studs of the steel extrusion become loose or break (due to fatigue), the Strip Seal Joint would get damaged and water leakage could occur. Therefore, anchorage integrity is a key aspect of the steel extrusion to ensure the functionality of the joint. The finite element model of the anchorage showed substantial safety margin when simulated with truck loading. The stresses in the block-out housing the anchorage is also very less.

4.3.2.3 Edge Protection

Similar to Compression Seal Joint, the condition of joint face is important for the Strip Seal Joint. If the edges are chipped off, water will penetrate through the interface of extrusion and concrete and thus accelerate deterioration by chemical or physical attacks (e.g., corrosion, and freeze and thaw). Furthermore, the eroded edges will expose the Strip Seal Joint to traffic load and the cyclic impact induced by it may damage the extrusion anchorage and concrete. To ensure the serviceability of the Strip Seal Joint, the concrete block-out must be strengthened. It must have high resistance to traffic load, corrosion, fracture and spalling. At the same time, it must form good bond with the steel extrusion to avoid air pockets and shrinkage cracks.

In current PennDOT practice, Class AAA-P concrete of strength close to 4000 psi is used. A recent study on concrete block-out (Distlehorst & Wojakowski, 2005) investigated the long-term performance of block-outs used in expansion joints in highway bridges. It is found that block-outs cast by Portland cement concrete are in good condition in the first 10 years. Then deterioration sets in. The main issue found in the block-outs is spalling. Significant spalling is developed in the block-outs soon after 10 years, which causes accelerated deterioration of the block-outs. Therefore, same lifespan may be expected for the concrete block-out made of Class AAA-P concrete in PennDOT.

In the same investigation (Distlehorst & Wojakowski, 2005), it is found that block-outs cast by elastomeric concrete display better performance. Negligible spalling is found in elastomeric concrete block-outs during first 10-year service. At same time, because of its excellent bonding with extrusion, it shows excellence in resisting shrinkage cracking, impacting and corrosion. This means it may have a longer service lifetime than block-outs made of Portland cement concrete. The only issue of elastomeric concrete is rutting, because its compression strength is lower than normal concrete. Currently, elastomeric concrete is used in MassDOT practice for Strip Seal Joint. To protect the block-out, MnDOT requires installing plow finger.

4.3.3 Summary of Expansion Joint

Based on the preceding analysis, the following evaluation may be obtained for expansion joints:

1. **Compression Seal Joint:**
   - The key working mechanism is the mobilizing friction on the joint surface. Therefore it is sensitive to skew angle. Large skew angle will generate significant shear force on the contact surface during thermal expansion, which causes slip of the neoprene seal.
   - Since there is no mechanical fixture to hold the neoprene seal and the friction is sensitive to slip, the Compression Seal Joint cannot carry significant push-out load. Therefore, it is susceptible to debris accumulation.
   - The friction requires good joint surface. Deformation like uneven settlement and rutting will raise the risk of joint damage. Therefore, strong concrete block-out is preferred for Compression Joint Seal.
   - If Compression Seal Joint is installed at the bottom, beneath the asphalt overlay, visual inspection of the Compression Seal is not possible.
2. **Strip Seal Joint:**
   - Experimental and computational investigations show that Strip Seal Joint has large safety margin to tolerate accidental load on strip seal and extrusion anchorage.

- The capacity of the strip seal to undergo large deformation enhances the joint's redundancy to debris accumulation.
- Block-out made of Portland cement concrete shows good performance for 10 years before deterioration sets in. Elastomeric concrete shows a longer service lifetime.
- Due to its installation location, Strip Seal Joint provides good access to visual inspection.

It can be seen Strip Seal Joints shows advantages in safety and robustness over Compression Seal Joint. In ODOT, the skew angle of Compression Strip Joint is limited to 15 degrees. In MnDOT, Compression Strip Joint is not used for expansion joint. In field visits in Pennsylvania, it is found Compression Seal Joint shows good condition only when the bridge span is short. The inspection reports from MnDOT and information from IDOT both show that Strip Seal Joint performs much better than Compression Seal Joint. Based on these observations, executable recommendations will be proposed for the expansion joints.

4.4 IN-SITU IMPLEMENATION

The waterproofing details given in PennDOT design and construction recommendations must be correctly implemented in practice. Otherwise, the waterproofing components cannot fulfill their expected functions. In addition, the incorrect implementation makes the evaluation of system safety and redundancy misleading, degenerated into a mathematical exercise with little practical value. Based on the in-situ observations, the following incorrect implementations found in the field visits severely impair the effectiveness and robustness of the waterproofing details:

1. **Delayed debris removal:** In Prospect #1 Bridge, it is found that a heap of debris, generated while resurfacing the deck for maintenance, was left on the bridge; see Fig. 4.16. The debris not only blocks the water discharge to form multiple ponds on the deck, but also accumulates on the expansion joint. Consequently, this delay of debris removal impairs the functionality of drainage system, causing a large amount of water to flow to the expansion joint. Furthermore, the accumulation of debris on the expansion joint also exposes the joints to jeopardy of impact by traffics.

2. **Incomplete protection of abutment:** Based on current PennDOT recommendations, the abutment seat must be protected by waterproofing membrane. However, in Boydstown Bridge and Little Connoquenessing Bridge, only waterstop between approach slab and abutment is used to prevent water from penetrating from backside of abutment. Moreover in the Little Creek Bridge, the membrane stops short of the bridge slab thus allowing for leakage at the beam – shear wall interface due to the failed expansion joint

Figure 4.16: Debris accumulation causing water ponding – Prospect #1 Bridge

3. **Bad quality control:** In the field visit of Little Creek Bridge, it was found that severe water penetration happened in the construction joints at the beam – shear wall interface. This means there were quality control issues in concrete casting, which voids the waterproofing system.

The aforementioned incorrect implementations narrow the safety margin of expansion joints, lower the redundancy of abutment waterproofing, and increase the risk of drainage dysfunction and joint damage. Therefore, they must be corrected in practice. For example, a strict timetable must be applied to the debris removal after deck repair.

4.5 WATER LEAKAGE DETECTION

One primary obstacle impedes realistic evaluation of current waterproofing practice is the lack of technical tools to accurately identify the sources (locations) of water leakage. As shown in Fig. 4.17, taken from current PennDOT practice, leakage found at abutment seat can be triggered by the failure in the Compression Seal Joint or the failure of the waterproofing membrane. However, none of them is accessible to inspection team because the joint is installed underneath the approach slab and the waterproofing membrane is covered by backfill. Without knowing the damage location, the failure mechanism of the corresponding waterproofing details can only be vaguely evaluated and the evaluation may be misleading. Furthermore, this obstacle makes it next to impossible to hold the incorrect implementation and bad quality control during construction *accountable*.

To improve the ability to identify the damage and failure location in waterproofing details in routine inspection, the following two strategies may be used in practice:

1. Enhancing the accessibility of waterproofing details to visual inspection;
2. Applying advanced technical tools to monitor inaccessible locations.

The accessibility of an expansion joint is largely related to its location, which is flexible compared to waterproofing membrane. If the expansion joint is installed on the top, instead of being covered by approaching slab, its accessibility to visual inspection will be dramatically improved. As shown in Fig. 4.17, the compression seal joint of Prospect #1 bridge is installed on the top and its in-situ condition can be easily evaluated by careful visual inspection, especially when water flows on it during rain. Thus, the adjustment of the joint location can significantly improve the inspection capacity of early damage detection, which makes it possible to repair the joints in a timely manner before any permanent damage on the abutment seat.

One concern of moving the expansion joint to the top is the possible damage induced by impact of traffic load and debris accumulation. This will be exacerbated if uneven settlement happens on the opposing sides of the expansion joint. However, this problem can be eliminated by using strong block-outs made of Portland cement concrete or elastomeric concrete on both sides of the joint.

As for the waterproofing membrane, its access to visual inspection cannot be improved because it must be covered by backfill. Therefore, advanced technical tools must be adopted to detect the water leakage in the waterproofing membrane. Currently, optical fiber sensor is a promising non-destructive approach, showing great potential and economical advantage in water leakage detection (Kaya et. al., 2013, Cho et. al., 2012). The working mechanism of optical fiber sensor is that the sensor reacts to humidity, temperature and other physical variations surround it by changing its refractive index, which can be monitored as light signal travels through the fiber.

Figure 4.17: Clear visibility of compression seal joint – Prospect #1 Bridge

Several optical fiber sensor systems, showing good results in experiments or real applications, are applicable to the waterproofing membrane in abutment system:

4.5.1 Optical fiber sensor combined with water combination soil (WCS):

The key component of this system consists of an optical fiber sensor and a vessel of water absorption material called WCS (Cho et. al., 2012); see Fig. 4.18. In implementation, this optical fiber sensor can be embedded between waterproofing membrane and abutment. If water leakage happens, the volume of WCS will change dramatically after it absorbs water. The signals input into the attached optical fiber which captures this volume change in WCS, and thus detects the water leakage. This system is effective and easy to use. The primary advantage, at the same time, also the main disadvantage of this system is that the WCS cannot recover its original shape after water absorption. Therefore, any water leakage happened will be permanently recorded in this system and there is no need for the inspection team to do the in-situ monitoring immediately after rain or snow. As a side effect, the sensor is not reusable in this system and thus cannot be used for long-term monitoring. A new sensor has to be installed for the next use.

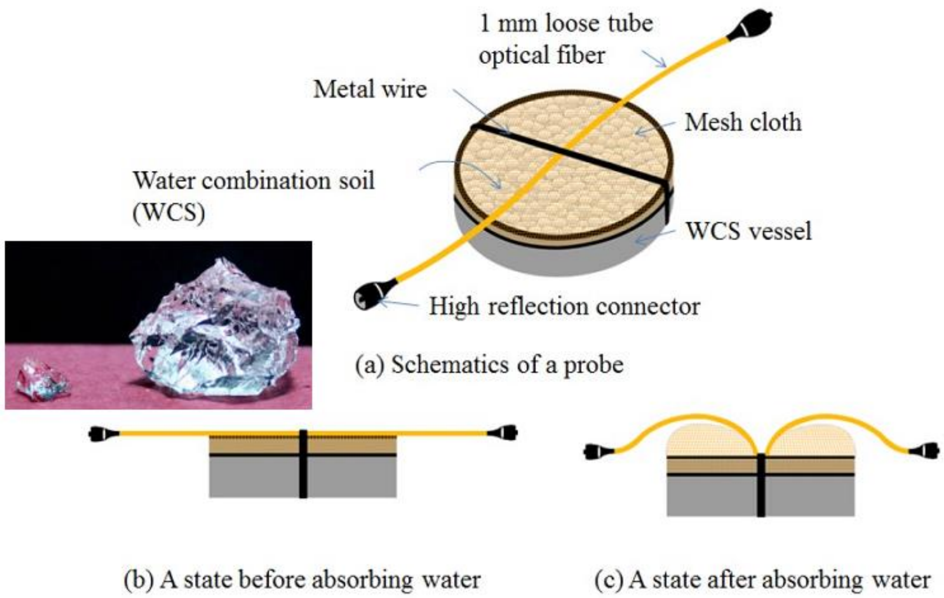


Figure 4.18: Configuration of a probe for water leak detection (Cho et al., 2012)

4.5.2 Evanescent Field-Fiber Loop Ringdown (EF-FLRD) sensor system:

This system consists of a fiber loop and a sensor head (Kaya et. al., 2013), as shown in Fig. 4.19. Different water content around the sensor head will affect the optical refractive index of the fiber loop. This leads to different ringdown times read by the data acquisition system. The fiber loop and sensor head can be easily embedded in the waterproofing membrane in implementation. If water leakage happens, the recorded ringdown signal will be different. In this system, the sensor head and fiber loop are reversible after surrounding humidity recovers. Therefore, this system is reusable and can be used to monitor the long-term performance of the waterproofing membrane. On the other hand, due to the reversibility of the sensor, the time window to detect the water leakage is limited and the inspection team has to conduct the monitoring during or immediately after the rain and snow.

Based on the advantages and disadvantages of these 2 systems, it is logical to use the WCS system to ensure the correct implementation, quality control and early age performance. For long-term monitoring, the EF-FLRD system will make a good choice.

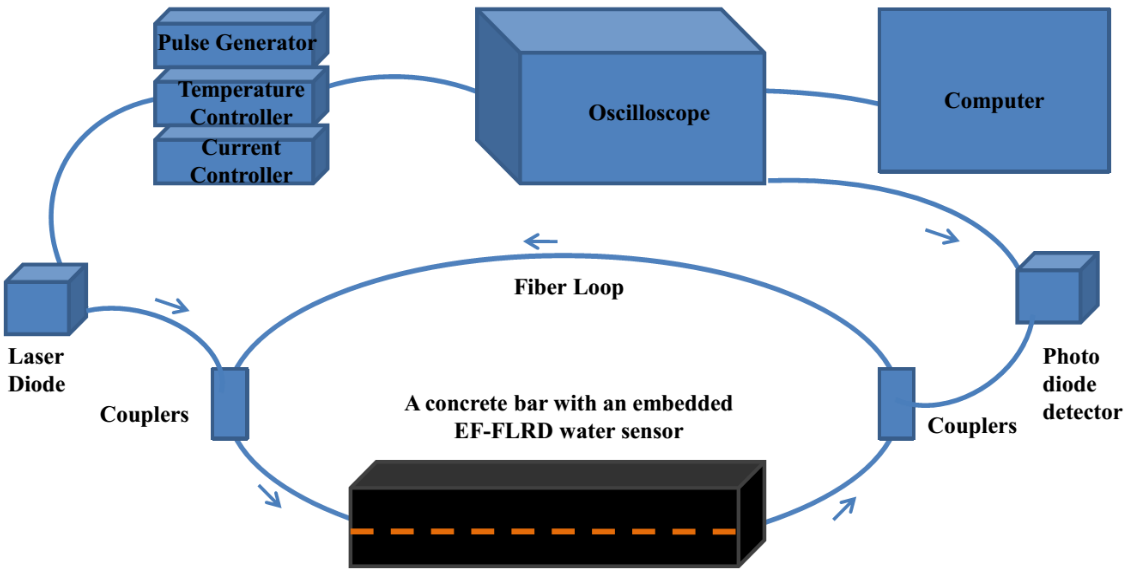


Figure 4.19: Schematic of an EF-FLRD water sensor unit (Kaya et al., 2012)

4.6 EXECUTABLE RECOMMENDATION

The evaluation on safety margin and redundancy of key components of waterproofing details provides valuable information for decision-making on improvement. Considering the lifecycle input including costs, labor and time in construction, inspection, maintenance and repair, it is logical to strengthen the abutment waterproofing to an extent as high as possible. This priority requires optimizing the structural configuration at the abutment seat to eliminate water leakage through the through-thickness gap. In addition, adding waterproofing membrane and drainage layer is preferable because it will enhance the redundancy of the system.

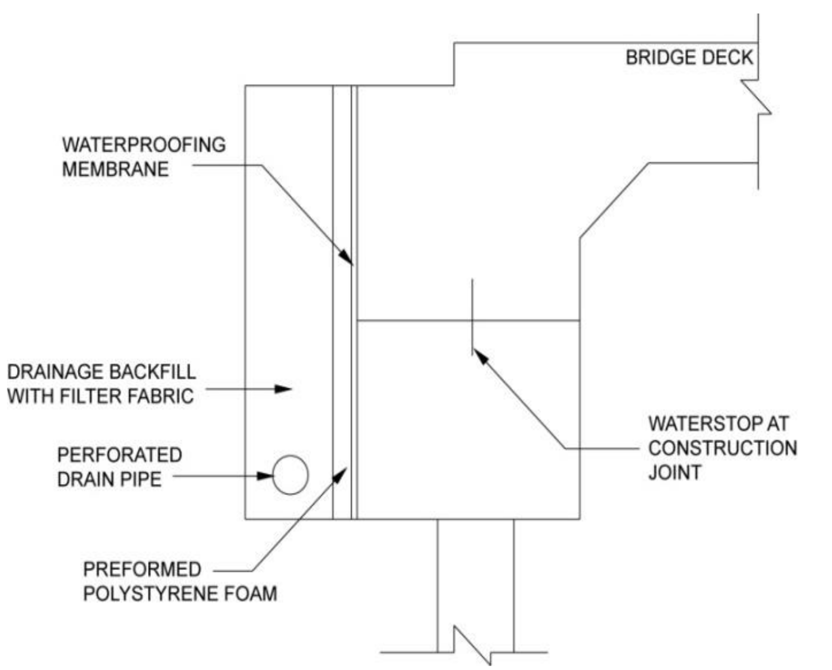
For expansion joints, the selection of joint type must take into account the service quality, construction and repair cost, and accessibility to visual inspection. Since the Compression Seal

Joint and Steel Seal Joint have different advantages and disadvantages, their usage in a given bridge must maximize the advantages and at the same time minimize the disadvantages. Based on evaluation and information from other states, the following recommendations can be drawn for the expansion joints:

1. Be accessible to visual inspection;
2. Limit the skew angle if Compression Seal Joint is used;
3. Select Steel Strip Joint for bridges of long spans and large skew angles;
4. Size the joint properly;
5. Use strong concrete, elastomeric concrete, or polymer-reinforced concrete for block-outs;

Following these recommendations, executable waterproofing details for integral abutment, parapet abutment, construction joint, old-new concrete interface, and abutment-wingwall joint are presented as follows:

<table>
<tr><td>Integral Abutment (highest priority)</td><td rowspan="2">Waterstop provided (crystalline waterstop is preferred);
Waterproofing membrane covering the backside of the breastwall with preformed polystyrene foam protection;
Drainage backfill with filter fabric, drained by a perforated drain pipe provided;</td></tr>
<tr><td>

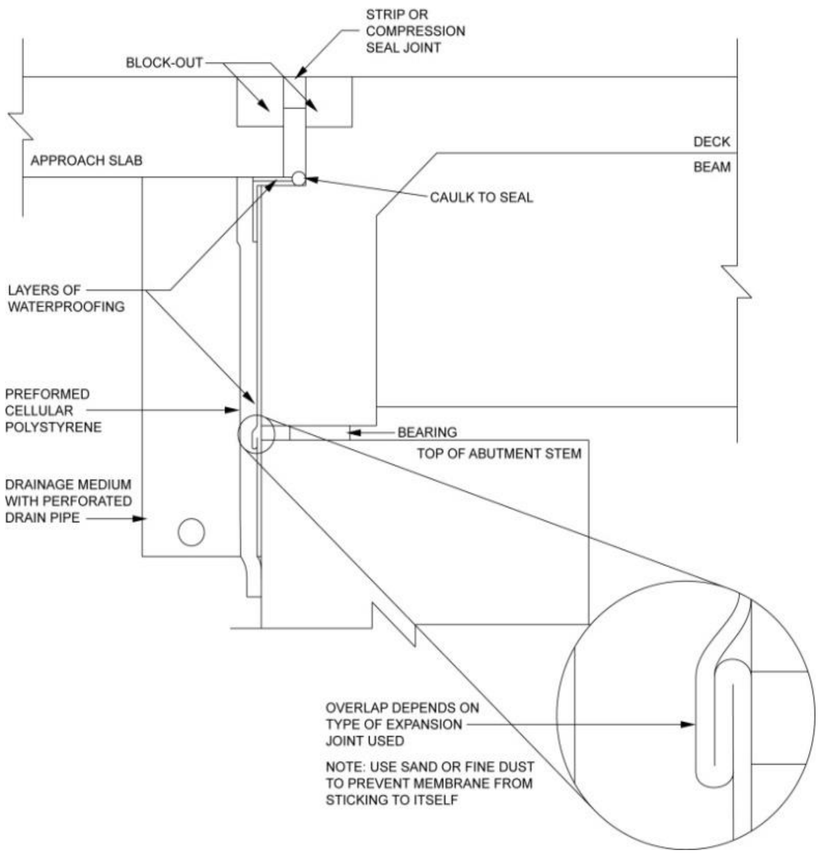


</td></tr>
<tr><td colspan="2">Whenever possible (usually span less than 100 ft.), integral abutment should be given the highest priority in selection of bridges. This is mainly due to its superior performance against leakage. For spans greater than 100 ft., factors such as soil strata, bridge skew, loading conditions, etc. need to be looked into. Redundancy of integral abutment is improved by adding waterstop, full height waterproofing membrane and drainage backfill.</td></tr>
</table>

<table>
<tr><td>Parapet abutment without backwall (joint on top of abutment, high priority)</td><td rowspan="2">

- A through-thickness gap at abutment seat;
- Expansion joint accessible for visual inspection;
- Strip Seal Joint for longer span and large skew angle;
- Compression Seal Joint for shorter span and small skew angle;
- Strong and durable block-out, to enhance its lifespan;
- Backup waterproofing membrane at the expansion joint;
- Waterproofing membrane extended to the abutment stem with extra length at abutment seat using polystyrene cover for protection;
- Drainage layer at abutment seat;
- Optical fiber sensor (WCS) embedded for quality control and early age performance evaluation;

</td></tr>
<tr><td>

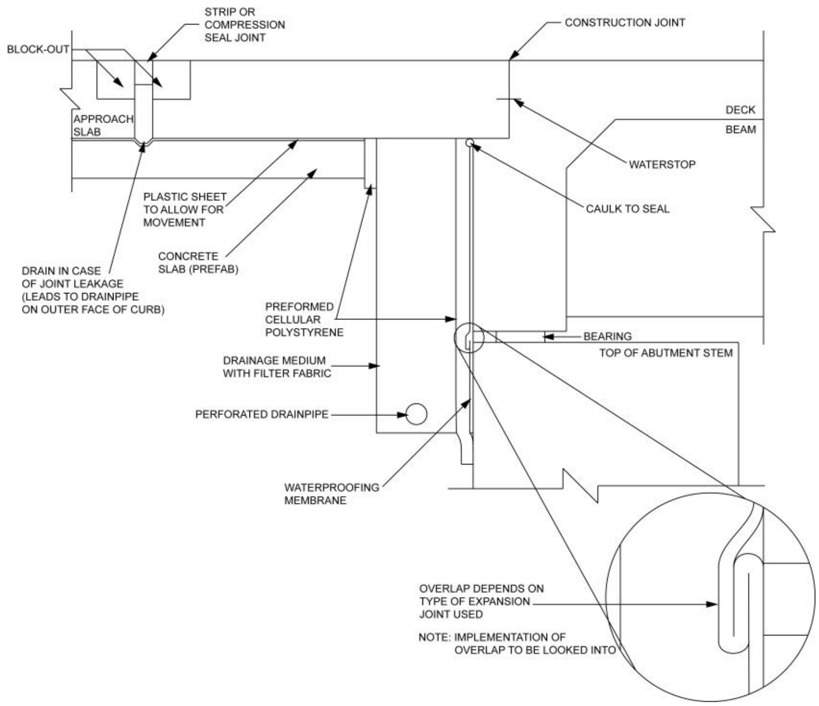


</td></tr>
<tr><td colspan="2">No dramatic change is made, when compared to the current practice in PennDOT, and is capable of placing the joints far from the deck ends. This implementation is recommended for spans greater than 100 ft. The safety and redundancy at abutment seat can be improved by mitigating the stress concentration in adhesive interface. By using strong block-out and backup membrane, the safety and redundancy at expansion joint is also improved. For compression seal joints, it is vital that size of the joint does not exceed predicted values and must be monitored. Method of overlap of membrane is merely speculative and must be explored. When bridge deck is extended to the approach slab, make sure the interface length of membrane is sufficient.</td></tr>
</table>

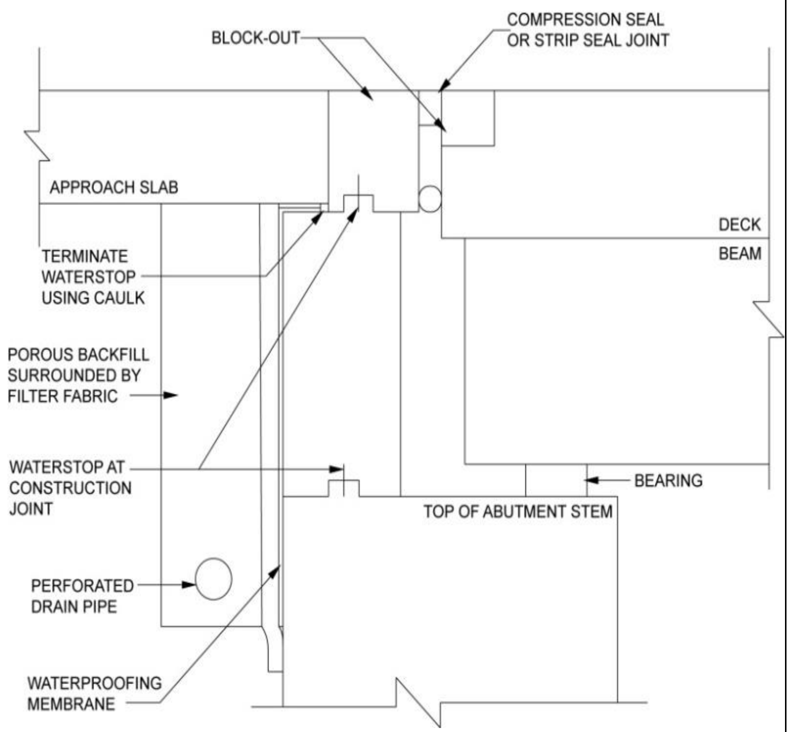
<table>
<tr><td>Parapet abutment without backwall (joint away from abutment, high priority)</td><td rowspan="2">

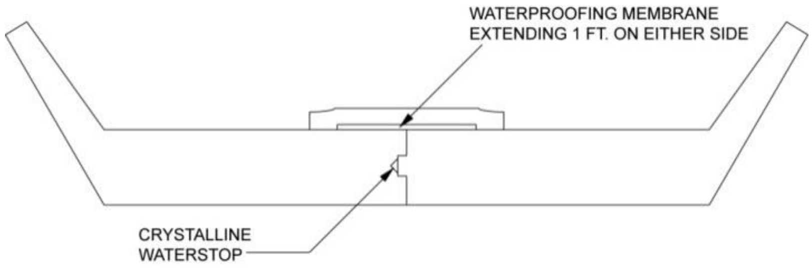
- A through-thickness gap at abutment seat;
- Expansion joint set away from the abutment;
- Expansion joint accessible for visual inspection;
- Strip Seal Joint for longer span and large skew angle;
- Compression Seal Joint for shorter span and small skew angle;
- Strong and durable block-out, to enhance its lifespan;
- Drainage under expansion joint, in support slab, for redundancy;
- Construction joint on top of abutment;
- Waterproofing membrane extended to abutment stem with extra length at abutment seat using polystyrene cover for protection;
- Drainage layer at abutment seat;
- Optical fiber sensor (WCS) embedded for quality control and early age performance evaluation;

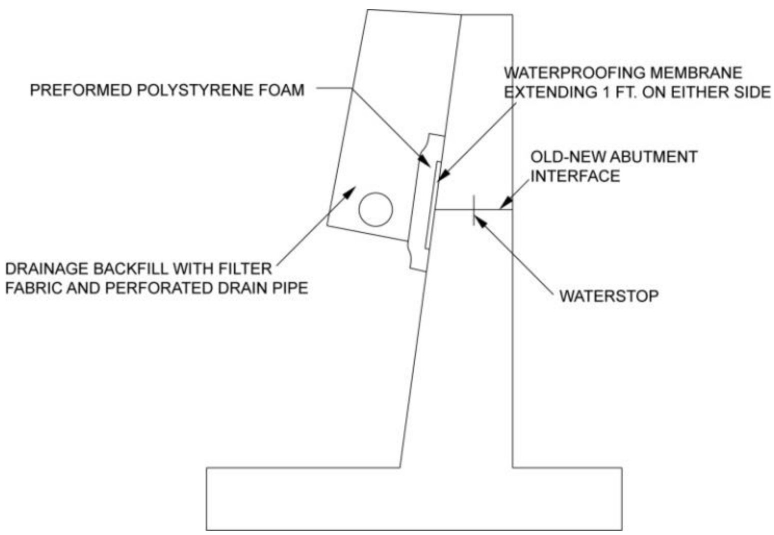
</td></tr>
<tr><td>

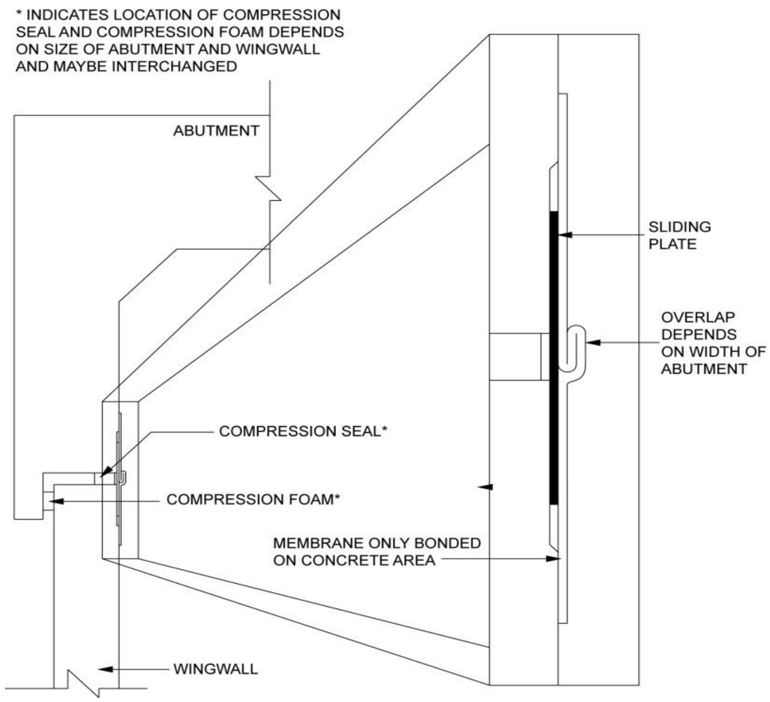


</td></tr>
<tr><td colspan="2">There are changes made, when compared to the current practice in PennDOT, by placing the joints far from the deck ends. This implementation is preliminarily recommended for spans less than or equal to 100 ft. By using strong block-out and backup membrane, the safety and redundancy at expansion joint is improved. For compression seal joints, it is vital that size of the joint does not exceed predicted values and must be monitored. Redundancy of expansion joint is improved by providing a drainage profile in the support slab. Construction/fabrication of the support slab requires good quality control to ensure smooth finishing of the sliding surface. The safety and redundancy at abutment seat can be improved by mitigating the stress concentration in adhesive interface. Method of overlap of membrane is merely speculative and must be explored. Further research is needed for this design detail due to insufficient data.</td></tr>
</table>

<table>
<tr><td>Parapet abutment with backwall (low priority)</td><td rowspan="2">• No through-thickness gap at abutment seat;
• Expansion joint accessible for visual inspection;
• Strip Seal Joint for longer span and large skew angle;
• Compression Seal Joint for shorter span and small skew angle;
• If using Compression Seal Joint, size of joint to be monitored (strain gauge or other devices);
• Strong and durable block-out, enhancing its lifespan;
• Waterstop at construction joints;
• Waterproofing membrane at construction joints with polystyrene cover for protection;
• Drainage layer at construction joints;</td></tr>
<tr><td>
</td></tr>
<tr><td colspan="2">Similar backwall details, used in MnDOT and NYDOT, show significant improvement in waterproofing. The water leakage from backside of abutment is substantially suppressed. This is recommended where backfill leakage is of high risk (for example, high water table). For compression seal joints, it is vital that the size of the joint not exceed predicted values and must be monitored to verify the difference between the designed limit and real movement. Disadvantage of this design detail is that, the expansion joint is located on top of the abutment.</td></tr>
</table>

Construction Joint	• Crystalline Waterstop provided; • Waterproofing membrane provided with polystyrene cover for protection; • Drainage layer (similar to that shown in Parapet abutment recommendations) provided;
	
Redundancy is improved by adding waterproofing membrane and drainage layer. Crystalline waterstop is suggested based on performance information available and should be investigated in this configuration.	

Old-new concrete interface	
	• Waterstop installed (crystalline waterstop preferred); • Waterproofing membrane provided; • Drainage layer added; • Optical fiber added;
Redundancy is improved by adding waterproofing membrane, waterstop and drainage layer. Membrane maybe extended to the top of the abutment. Optical fiber is implemented, at the interface, to monitor the quality control and membrane damage.	

Abutment-wingwall joint	
	• Sharp angle at joint to be avoided; • Waterproofing membrane provided with overlap; • Compression seal and compression foam provided for water tightness; • Location of compression seal and compression foam depend on width of the abutment and wingwall; • Compression seal accessible for visual inspection; • Sliding plate to prevent damage to membrane
For small movement at joint, compression seal is used to strengthen the waterproofing capacity and its accessibility for visual inspection is enhanced.	

The executable waterproofing details recommended here are based on literature review, field visits, inspection reports and structural evaluation, as well as supplemented by information obtained from other states and analytical research. Therefore, their real effectiveness and robustness need to be probed based on the performance in practice.

APPENDIX A

SPECIFICATIONS

State drawing details: All latest drawings taken from the websites as of June 01, 2013

1. MnDOT
    a. Waterproof Expansion Device (With type F barrier), Fig. 5-397.627
    b. Waterproof Expansion Device Snow Plow protection, Fig. 5-397.628
    c. Waterproof Expansion Device (With raised median or sidewalk), Fig. 5-397.630
    d. Pavement Joints, Sheet no. 5-297.221
    e. Bridge Floor Drain (Welded Box), Detail no. B701
    f. Bridge Floor Drain (Structural Tube), Detail no. B702
    g. Bridge Offset Floor Drain (Welded Box), Detail no. B705
    h. Bridge Offset Floor Drain (Structural Tube), Detail no. B706
    i. Drainage System, Detail no. B910
    j. Bridge Abutment Approach Treatment, Sheet no. 5-297.234
    k. Bridge Approach Panel Drainage details, Sheet no. 5-297.231
2. ODOT
    a. Typical Abutment Details for Steel beam and girder bridges, A-1-69
    b. Compression Seal Expansion joints at abutments for Steel stringer structures, EXJ-2-81
    c. Compression Seal Expansion joints at abutments for Prestressed box beam structures, EXJ-3-82
    d. Strip Seal Expansion joints for Steel stringer structures, EXJ-4-87
    e. Strip Seal Expansion joints for Concrete box beam structures, EXJ-5-93

f. Strip Seal Expansion joints for Concrete I-beam superstructures, EXJ-6-06
g. Polymer Modified Asphalt Expansion joint system
h. Integral Construction details for Steel beam and girder bridges on flexible abutments, ICD-1-82
i. Semi-Integral Construction details for Steel beam and girder bridges on rigid abutments, SICD-1-96

APPENDIX B

TABLES

Table B1: Weather Data from NOAA (2009)

	1	2	3	4	5	6	7	8	9	10	11	12
Average Monthly Temperature (F)												
Pittsburgh	22.0	31.2	42.3	52.1	61.2	68.2	69.4	71.8	64.9	50.7	47.2	31.1
Boston	20.2	30.3	35.5	49.2	57.8	63.3	70.5	73.6	63.2	51.9	48.8	33.2
Minneapolis	8.3	20.8	32.2	47.6	60.8	67.7	70.0	69.4	66.5	43.2	42.7	17.3
Columbus	22.6	33.8	46.0	53.4	63.5	72.2	71.0	72.6	66.8	51.6	47.8	32.2
Average Monthly Precipitation (in.)												
Pittsburgh	2.98	1.56	1.69	2.36	3.83	4.42	4.12	3.55	1.55	2.29	0.96	3.53
Boston	3.36	1.72	2.19	4.21	3.63	3.22	6.90	3.24	3.09	5.17	3.34	3.91
Minneapolis	0.57	0.93	1.50	1.57	0.53	2.86	2.17	6.43	0.46	5.57	0.38	1.83
Columbus	2.73	1.93	1.15	4.23	2.42	3.44	4.90	3.27	2.50	4.89	0.42	3.60
Average Monthly Snow (in.)												
Pittsburgh	20.8	7.1	0.2	1.3	0.0	0.0	0.0	0.0	0.0	T	T	10.8
Boston	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	15.2
Minneapolis	8.4	10.9	1.5	2.5	0.0	0.0	0.0	0.0	0.0	2.8	T	20.9
Columbus	20.0	0.2	T	0.1	0.0	0.0	0.0	0.0	0.0	0.0	T	8.9
Monthly Occurrence of Precipitation > 0.01 in. (days)												
Pittsburgh	17	11	9	16	14	13	11	8	11	13	10	18
Boston	9	7	10	13	17	16	13	9	5	12	10	11
Minneapolis	9	6	6	8	6	12	12	10	3	17	7	10
Columbus	16	6	7	13	9	11	12	9	13	13	8	14

Table B2: Weather Data from NOAA (2010)

	1	2	3	4	5	6	7	8	9	10	11	12
Average Monthly Temperature (F)												
Pittsburgh	25.9	26.4	43.3	55.4	63.6	70.8	75.6	74.4	65.7	53.4	42.3	25.6
Boston	29.6	33.2	43.9	53.0	62.8	70.3	77.2	73.4	68.7	55.6	44.8	32.7
Minneapolis	13.0	19.7	41.0	54.9	60.7	69.2	76.3	77.0	60.2	54.0	35.3	16.4
Columbus	26.0	26.7	44.2	58.1	65.6	74.3	77.0	76.3	68.4	56.2	43.7	26.5
Average Monthly Precipitation (in.)												
Pittsburgh	2.90	3.22	2.19	1.76	5.19	5.13	2.86	1.68	3.27	2.12	5.97	1.56
Boston	2.91	3.34	14.87	1.78	2.90	3.18	2.66	5.75	1.80	3.90	2.96	3.61
Minneapolis	0.45	0.75	0.69	2.32	2.50	6.25	3.03	4.91	5.53	1.61	2.07	2.79
Columbus	2.22	2.42	2.75	2.51	3.89	5.38	6.01	2.23	1.66	1.54	4.34	1.26
Average Monthly Snow (in.)												
Pittsburgh	17.4	48.7	0.5	T	0.0	0.0	0.0	0.0	0.0	0.0	T	12.2
Boston	13.2	7.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	22.0
Minneapolis	3.1	13.9	0.0	0.0	T	T	0.0	0.0	T	T	9.8	33.6
Columbus	10.9	30.1	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	T	7.3
Monthly Occurrence of Precipitation > 0.01 in. (days)												
Pittsburgh	15	18	10	7	12	15	9	8	11	10	9	15
Boston	8	7	14	9	8	12	9	7	9	11	9	9
Minneapolis	6	9	6	9	11	16	11	6	10	5	11	12
Columbus	14	12	11	7	17	14	9	5	8	10	10	12

Table B3: Weather Data from NOAA (2011)

	1	2	3	4	5	6	7	8	9	10	11	12
Average Monthly Temperature (F)												
Pittsburgh	24.2	31.8	39.2	53.3	62.9	70.0	76.9	72.8	65.4	52.8	46.9	37.5
Boston	27.6	30.5	38.9	50.1	59.2	67.1	77.3	73.9	67.3	57.5	50.4	40.1
Minneapolis	12.0	18.7	29.4	46.2	58.4	69.5	78.8	73.6	62.9	55.3	39.2	27.8
Columbus	24.5	32.6	41.1	55.0	64.2	72.5	80.2	74.5	65.6	54.6	48.7	38.9
Average Monthly Precipitation (in.)												
Pittsburgh	2.41	4.97	4.99	5.13	4.58	2.50	2.62	2.69	3.73	4.40	3.75	2.47
Boston	4.57	4.57	2.10	4.04	3.23	4.76	2.04	7.74	4.40	6.77	4.21	3.96
Minneapolis	1.00	1.12	2.06	2.80	4.04	5.28	5.23	3.03	0.36	0.70	0.30	0.99
Columbus	1.47	4.25	4.58	7.14	5.90	3.03	5.67	2.48	6.55	3.68	4.77	5.44

Table B3: (continued)

Average Monthly Snow (in.)												
Pittsburgh	24.1	14.1	5.5	0.8	0.0	0.0	0.0	0.0	0.0	1.6	T	1.2
Boston	38.3	18.5	1.3	0.9	0.0	0.0	0.0	0.0	0.0	1.0	T	T
Minneapolis	17.0	16.1	8.2	1.9	T	0.0	0.0	0.0	0.0	0.0	3.0	7.3
Columbus	13.3	4.8	3.3	T	0.0	0.0	0.0	0.0	0.0	0.0	T	0.5
Monthly Occurrence of Precipitation > 0.01 in. (days)												
Pittsburgh	22	13	13	18	17	13	9	10	18	15	13	15
Boston	11	10	9	16	13	13	10	14	11	13	7	11
Minneapolis	16	8	11	12	16	11	10	9	5	5	3	10
Columbus	15	11	12	19	16	15	10	7	17	13	10	15

Table B4: Weather Data from NOAA (2012)

	1	2	3	4	5	6	7	8	9	10	11	12
Average Monthly Temperature (F)												
Pittsburgh	32.8	35.4	51.5	50.4	67.0	70.1	76.8	71.5	63.6	53.5	39.6	38.1
Boston	34.1	37.3	46.7	53.1	60.3	66.8	75.3	74.6	64.7	56.5	42.1	38.4
Minneapolis	23.3	27.7	48.3	50.0	63.7	72.3	80.2	72.0	63.9	47.5	37.1	23.4
Columbus	51.9	54.9	66.8	67.8	76.1	79.4	84.2	80.6	76.8	66.9	55.7	54.1
Average Monthly Precipitation (in.)												
Pittsburgh	3.85	2.24	3.29	1.31	4.69	1.24	7.32	2.65	4.80	4.44	0.38	5.53
Boston	2.67	1.00	1.21	3.09	3.43	4.71	3.88	3.08	4.10	2.62	1.01	5.93
Minneapolis	0.36	1.71	1.40	3.04	9.34	3.59	4.90	1.38	0.30	1.30	0.63	1.64
Columbus	5.46	3.64	3.88	0.49	3.34	2.18	2.92	2.30	3.60	1.04	1.13	5.23
Average Monthly Snow (in.)												
Pittsburgh	15.8	12.3	6.0	T	0.0	0.0	0.0	0.0	0.0	T	0.8	13.7
Boston	5.0	34.0	20.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	3.4
Minneapolis	4.6	15.1	13.8	17.9	0.5	0.0	0.0	0.0	0.0	0.0	0.8	15.0
Columbus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Monthly Occurrence of Precipitation > 0.01 in. (days)												
Pittsburgh	18	12	13	10	9	9	12	11	13	13	6	19
Boston	14	6	8	6	13	13	8	7	11	16	5	15
Minneapolis	8	7	12	13	15	9	9	10	3	7	7	9
Columbus	13	10	9	4	9	5	11	11	11	3	4	10

Table B5: PennDOT Rating Code

Rating		Explanation
N	Not Applicable	
9	Excellent Condition	
8	Very Good Condition	No problems noted
7	Good Condition	Some minor problems
6	Satisfactory Condition	Structure elements show some minor deterioration
5	Fair Condition	All primary structure elements are sound but may have minor section loss, cracking, spalling or scour
4	Poor Condition	Advanced section loss, deterioration, spalling or scour
3	Serious Condition	Loss of section, deterioration, spalling or scour may have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present
2	Critical Condition	Major structural defects, components have moved to point of possible collapse
1	“Imminent” Failure Condition	Major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service
0	Failed Condition	Out of service – Beyond corrective action

Table B6: ODOT Rating for Full Height Concrete Abutment

<table>
<tr><th colspan="2" rowspan="2">Rating</th><th>Spalling with Exposed Reinforcement</th><th>Damp or Dark Areas</th><th rowspan="2">Cracking and Rotation</th></tr>
<tr><th colspan="2">Percentage of Area</th></tr>
<tr><td rowspan="3">1</td><td>Excellent</td><td colspan="3">No signs of distress, no discoloration</td></tr>
<tr><td>Very Good</td><td>Minor delamination, minor spalling</td><td>Minor discoloration</td><td>Isolated hairline cracking with no rust staining, no dampness, no leakage</td></tr>
<tr><td>Good</td><td>**Up to 1%**</td><td>**Up to 5%**</td><td>Minor problems, hairline cracking with isolated leaking, efflorescence, no rust staining</td></tr>
<tr><td rowspan="2">2</td><td>Satisfactory</td><td>**Up to 5%** (unsound areas up to 10%)</td><td>**Up to 10%**</td><td>Minor structural cracking with leaking, efflorescence and rust staining</td></tr>
<tr><td>Fair</td><td>**Up to 10%** (unsound areas up to 20%)</td><td>**Up to 20%**</td><td>Structural cracking with leaking, efflorescence and rust staining, Measurable, minor rotation or settlement</td></tr>
<tr><td rowspan="2">3</td><td>Poor</td><td colspan="2">**Combined total not exceeding 30%** with more than 4 adjacent exposed reinforcing bars having greater than 10% section loss to the original diameter</td><td>Advanced cracking with heavy leaking, efflorescence and rust staining; Differential settlement up to 1”</td></tr>
<tr><td>Serious</td><td colspan="3">**Up to 30%** spalling, delamination with more than 5 adjacent reinforcing bars have greater than 25% section loss to the original diameter OR **Up to 50% damp/dark areas**, significant differential settlement (up to 2” vertical, or up to 4” horizontal)</td></tr>
<tr><td rowspan="3">4</td><td>Critical</td><td colspan="3">**More than 30%** spalling, delamination with more than 10 adjacent reinforcing bars having greater than 25% section loss to the original diameter OR **More than 50% damp/dark areas**; Extreme settlement (greater than 2” vertical or greater than 10% of the height; horizontal movement up to 4” max). Any adjacent vertical bars bent or cracked or severed</td></tr>
<tr><td>Imminent Failure</td><td colspan="3">Major deterioration in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but correction action may put back in light service.</td></tr>
<tr><td>Failure</td><td colspan="3">Bridge closed, collapsed</td></tr>
</table>

Table B7: ODOT Rating for Stub Abutment (use in conjunction with Concrete "Cracks" column in Table B5)

Rating		Spalls/Unsound areas
1	Excellent	No Spalls
	Very Good	No dampness, no leakage, no spalling, no reinforcement visible
	Good	A few spalls or unsound areas, some cover missing, exposed reinforcement visible, less than ½ width of one substructure unit
2	Satisfactory	Up to 4" deep spall for less than 1/2 of bridge width
	Fair	Up to 4" deep spall for more than 1/2 of bridge width OR 100% saturation with full width delaminations with a few exposed vertical bars
3	Poor	Up to 6" deep spall for more than 1/2 of bridge width; reinforcing bars have extensive section loss (greater than 10% of original diameter) for more than 4 adjacent bars OR 100% saturation with full width delaminations with many exposed vertical bars
	Serious	Up to 8" deep spall for more than 1/2 of bridge width; reinforcing bars have extensive section loss (greater than 20% of original diameter) for more than 5 adjacent bars
4	Critical	Up to 8-9" deep spall for more than 1/2 of bridge width; reinforcing bars have extensive section loss (greater than 30% of original diameter) for more than 10 adjacent bars OR Bent or broken adjacent vertical bars. Any section under traveled lane where approach backfill is spilling through
	Imminent Failure/Failed	More than 9" deep spall for more than 1/2 of bridge width; reinforcing bars have extensive section loss (greater than 30% of original diameter) for more than 10 adjacent bars OR Bent or broken adjacent vertical bars. Any section under traveled lane where approach backfill is spilling through

Table B8: ODOT Rating for Backwall

Rating		Deterioration/Deficiencies
1	Excellent	No Deficiencies
	Very Good	Minor deterioration (ex. Hairline cracking)
	Good	Minor deterioration (ex. Cracking)
2	Satisfactory	Moderate deterioration (ex. Cracking, isolated discoloration, some beam-touching in warmer temperatures)
	Fair	Moderate deterioration (ex. Cracking, isolated discoloration, Backwall touching in colder temperatures)
3	Poor	Advanced deficiencies (ex. structural cracks with leakage from beams touching, 2 non adjacent bays with heavy spalling)
	Serious	Advanced deficiencies (e.g. structural cracks in more than one bay allowing moisture infiltration, backwall sheared in 2 adjacent bays with heavy spalling and heavy steel section loss)
4	Critical	1 bay allowing approach-fill onto seats; Multiple bays with heavy spalling and infiltration. Backwall sheared and displaced due to beam contact
	Imminent Failure/Failed	Any worse than above

Table B9: ODOT Rating for Expansion Joints

Rating		Runoff	Expansion and Contraction opening	Armor and Anchorage
1	Excellent	No Leakage		
	Very Good	Minor isolated leakage the joint, debris may be present	Measurements exhibit normal expansion and contraction	Minor surface delaminations in header
	Good	Localized signs of leakage along the joint may be present, debris	Measurements exhibit normal expansion and contraction	A few delaminations or spalls or cracking in the header
2	Satisfactory	Leakage in several places. Gland is partially separated from the armor or has minor tears. Significant debris	Minor abnormalities in the longitudinal measurements may exist	Spalls or cracking in the deck and/or header may be present adjacent to the joint. Gouges in armor
	Fair	Excessive leakage along the joint in many locations. Gland may be partially pulled out of the extrusion. paved over	Abnormalities in measurements. Bent or misaligned fingers may be observed. Minor vertical offset; Note this is more important where plow catch points exist	'Clanking' under heavy truck traffic only with small spalls or cracking. Gouges in armor
3	Poor	Gland has been pulled completely out of the extrusion.	Significant abnormalities in the measurements. Missing or broken fingers. Up to 1" vertical misalignment (plow catch point)	Clanking in one lane under truck traffic. Major spalls or significant cracking
	Serious		Major abnormalities in the measurements, up to 2" misalignment (plow catch points)	Visible movement and clanking under all traffic loads in one lane, major spalls
4	Critical	Major abnormalities in the longitudinal, vertical and/or horizontal measurements, greater than 2" misalignment (plow catch points exist).Tight on one side and open in the other. Visible movement and clanking under all traffic loads in all lanes, major spalls. Anchorage separation on multiple beams.		

Table B10: ODOT Rating of Drainage

Rating		General	Clogging	Ponding
1	Excellent	New, No problems noted		
	Very Good	All of runoff is getting off of the deck, minor scattered problems		
	Good	All of runoff is getting off of the deck with minor deficiencies to drainage system.		
2	Satisfactory	Most of the water getting off of deck with minor deficiencies to drainage system	Few scuppers continually clog	Minor ponding along the curb line
	Fair	All primary structural elements are sound but have minor section loss, deterioration or spalling	Up to a quarter of scuppers/grates continually clog	Minor ponding may exist in the shoulder or outside of the traveling lanes
3	Poor	Advanced section loss or deterioration affecting the structure	Up to half of the scuppers/grating continually clog	Ponding is beginning to cross into the traveling lane
	Serious	Loss of section or deterioration has seriously affected primary structural components. Local failures of the drainage system	More than half of the scuppers/grating continually clog	Significant ponding into the traveling lane with potential for hydroplaning or icing
4	Critical	Unless closely monitored it may be necessary to close the lane(s) until corrective action is taken. Local flooding, hydroplaning or icing due to improper drainage system		
	Imminent Failure	Major deterioration, lane closures exist due to drainage but corrective action may put back in light service		
	Failed	Out of service - beyond corrective action		

Table B11: MnDOT Rating for Reinforced Concrete Abutment

Condition State	Remarks
1	Reinforced concrete abutment has little or no deterioration. There may be minor cracking, leaching, staining, or surface scale - there is no notable delamination or spalling. The abutment wall has no impact damage or repair patches
2	Reinforced concrete abutment has minor to moderate deterioration. There may be moderate cracking, leaching, staining, or surface scale. Minor delamination or spalls may be present, but there is little or no exposure of steel reinforcement. Element is in proper position and alignment – all connections are sound. Repair patches (if any) remain sound.
3	Reinforced concrete abutment has extensive deterioration, but the load-carrying capacity of the abutment has not been significantly reduced. There may be extensive cracking, leaching, staining, or scale. Structural cracking (from shear or flexure) may be present. Delamination and spalls may be prevalent. Exposed reinforcement may have corrosion, but any section loss is incidental and does not significantly affect the strength and/or serviceability of either the abutment or the bridge. Abutment may be slightly out of position or alignment - connections may have started to come loose
4	Reinforced concrete abutment has severe or critical deterioration. The load-carrying capacity of the abutment has been significantly reduced - structural analysis or immediate repairs may be required. Severe structural cracking (from shear or flexure) may be present. Spalling may be extensive or severe - exposed reinforcement may have significant section loss. The abutmentmay be severely damaged or significantly out of position or alignment - connections may have failed

Table B12: MnDOT Rating for Strip Seal Joint

Condition State	Remarks
1	Strip seal joint has little or no deterioration (no leakage). Gland is sound and securely anchored. Joint anchorage and adjacent deck remain sound and intact. Joint is properly aligned and functioning as intended. Debris in the joint (if any) is not causing any problems
2	Strip seal joint has moderate deterioration - minor leakage may be evident. Gland may be partially pulled out. Joint anchorage may be slightly damaged. Adjacent deck may have minor spalling. Joint may be slightly misaligned (skewed, offset, or near limits of expansion), but the function has not been significantly impaired. Debris in the joint may be causing problems
3	Strip seal joint has severe deterioration - there may be significant leakage. Gland may be punctured, torn, or pulled loose. The joint anchorage may be damaged or deteriorated to the extent that the gland can no longer be properly anchored. Adjacent deck may have severe spalling. Joint may be severely misaligned - the function may be significantly impaired

Table B13: MnDOT Rating for Compression Seal Joint

Condition State	Remarks
1	Compression joint has little or no deterioration (no leakage). Compression seal is sound and securely anchored. Protection angles (if present) are in good condition. Adjacent deck remains sound and intact. Joint is properly aligned and functioning as intended. Debris in the joint (if any) is not causing any problems
2	Compression joint has moderate deterioration (minor leakage may be evident). Compression seal may be slightly loose or out of position. Protection angles may have minor damage. Adjacent deck may have minor spalling. Joint may be slightly misaligned (skewed, offset, or near limits of expansion), but the function has not been significantly impaired. Debris in the joint may be causing problems
3	Compression joint has severe deterioration (there may be significant leakage). Compression seal may be punctured, torn, or out of position. Protection angles may have severe damage. Adjacent deck may have severe spalling. Joint may be severely misaligned - joint function may be significantly impaired

Table B14: MnDOT Rating for MBEJ

Condition State	Remarks
1	Modular joint has little or no deterioration (no leakage). Seals are sound and securely anchored. All joint components (extrusion/joint anchorage, support beams, equalizers, and guide systems) are sound and intact. Adjacent deck is sound. Joint is properly aligned and functioning as intended. Debris in the joint (if any) is not causing any problems
2	Modular joint has moderate deterioration - minor leakage may be evident. Seals may be partially pulled out, slightly loose or out of position. Joint equalizers (or guide system components) may be loose, damaged or missing. Joint support beams remain sound and intact. The joint anchorage may be slightly damaged. Adjacent deck may have minor spalling. Joint may be slightly misaligned (skewed, offset, or near limits of expansion), but the function has not been significantly impaired. Debris in the joint may be causing problems
3	Modular joint has severe deterioration - there may be significant leakage. Seals may be punctured, torn, pulled loose, or out of position. Joint equalizer/guide system may be severely deteriorated or no longer functioning. Support beams may be loose, jammed, or otherwise inoperative. Joint anchorage may be damaged or deteriorated to the extent that the gland can no longer be properly attached. Adjacent deck may have severe spalling. Joint may be severely misaligned - joint function may be significantly impaired

Table B15: MnDOT Rating for Finger Plate Joint

Condition State	Remarks
1	Finger plate joint has little or no deterioration. Expansion plates are securely anchored (all fingers are intact). Adjacent deck is sound. Joint is properly aligned and functioning as intended
2	Finger plate joint has moderate deterioration. Some fingers may be broken off. Expansion plates may have started to loosen - some anchor bolts may be loose, broken or missing (welds may have broken). Adjacent deck may have minor spalling. Joint may be slightly misaligned (skewed, offset, or near limits of expansion), but the function has not been significantly impaired
3	Finger plate joint has severe deterioration. A significant number of fingers may be broken off. Expansion plates may be loose or missing - a large number of anchor bolts may be loose, broken or missing. Adjacent deck may have severe spalling. Joint may be severely misaligned – joint function may be significantly impaired

Table B16: MnDOT Rating for Deck and Approach Drainage

Condition State	Remarks
1	Drainage system is in good condition and functioning as intended. There is no notable ponding or drainage-related slope erosion
2	Drainage system is inadequate or is not functioning properly. The drainage system may be clogged with debris - flushing or cleaning may be required. There may be ponding on the deck, approaches, or below the bridge. Runoff may be contributing to slope erosion or deterioration of bridge elements. Drainage components may be damaged or deteriorated, but remain intact
3	Drainage system has failed - repairs are required. Severe ponding may present a traffic hazard. Runoff may have resulted in severe slope erosion (or significant deterioration of bridge elements). Drainage components may be disconnected, missing, or severely deteriorated

APPENDIX C

ADDITIONAL FIGURES

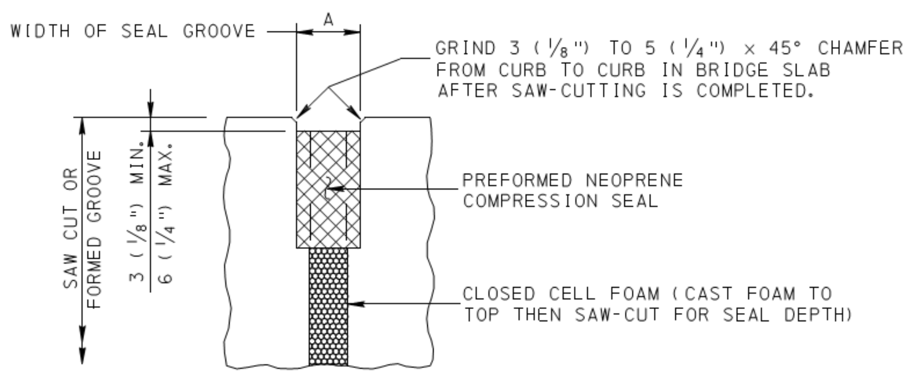


Figure C1: PennDOT compression seal joint

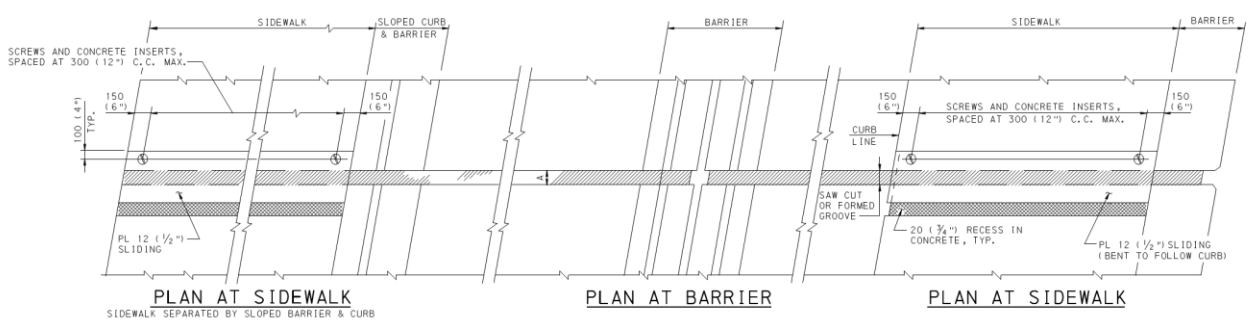


Figure C2: PennDOT plan of compression seal joint

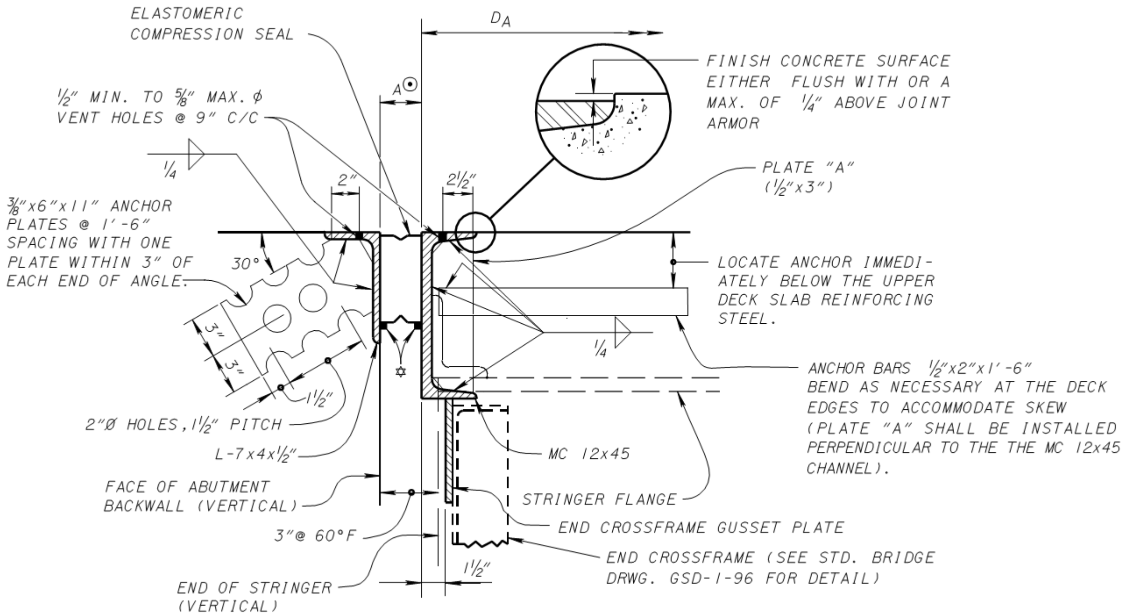


Figure C3: ODOT detail of compression seal joint (steel stringer bridge)

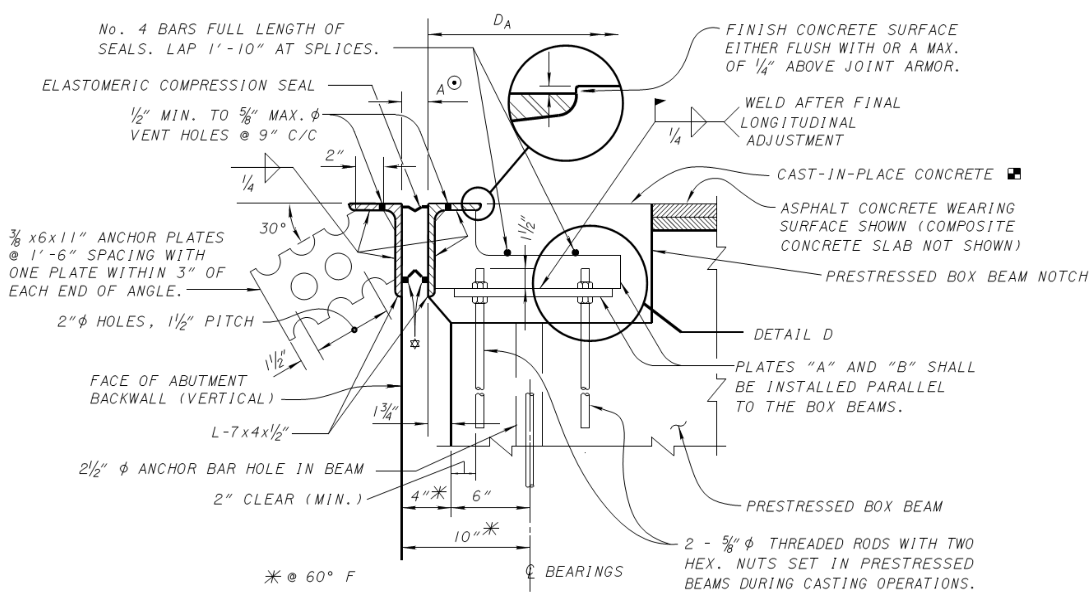


Figure C4: ODOT detail of compression seal joint (prestressed box beam bridge)

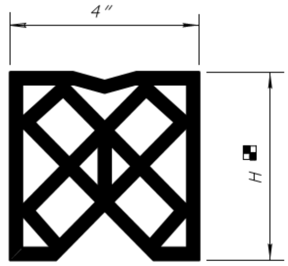


Figure C5: ODOT compression seal design

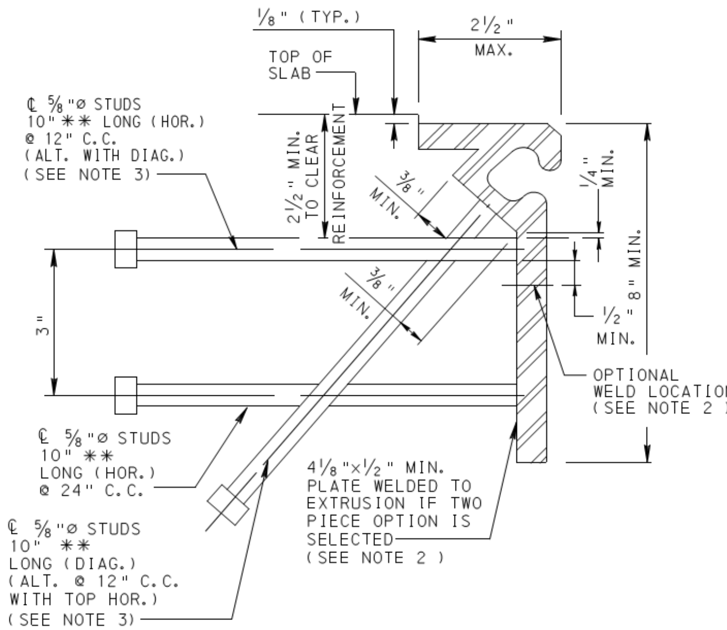


Figure C6: PennDOT steel extrusion design

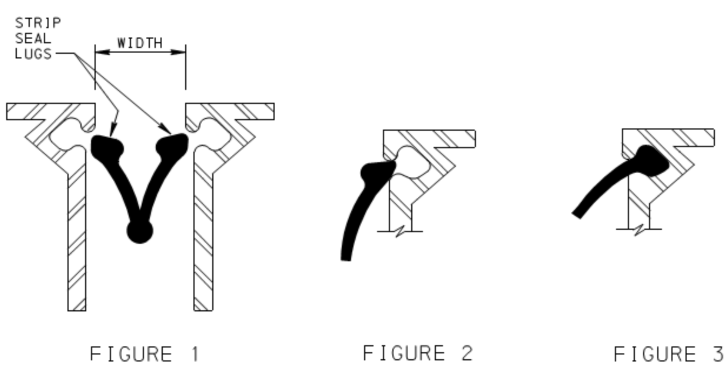


Figure C7: PennDOT strip seal installation procedure

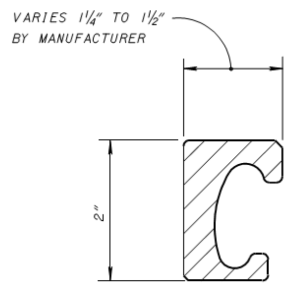


Figure C8: ODOT steel extrusion design

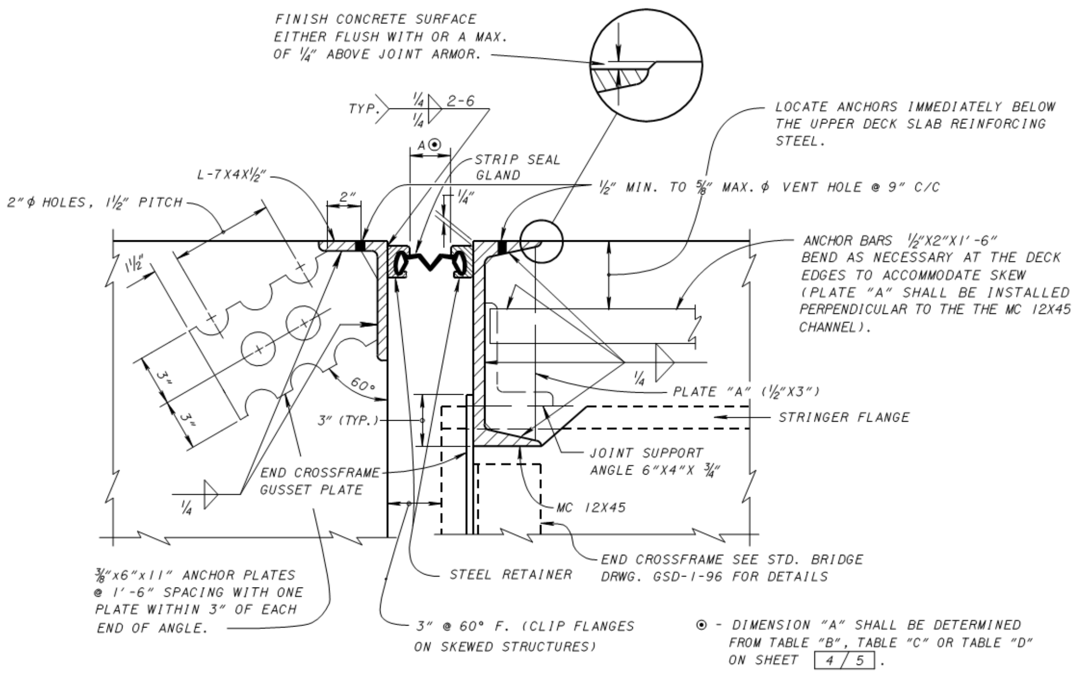


Figure C9: ODOT strip seal joint detail (steel stringer bridge)

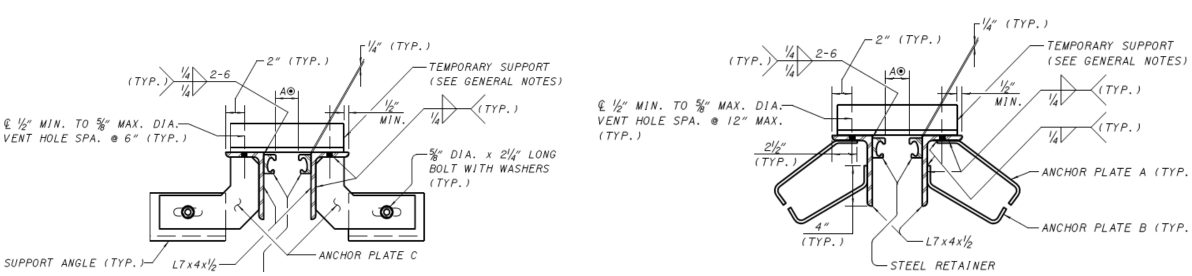


Figure C10: ODOT strip seal joint design (Concrete I-beam)

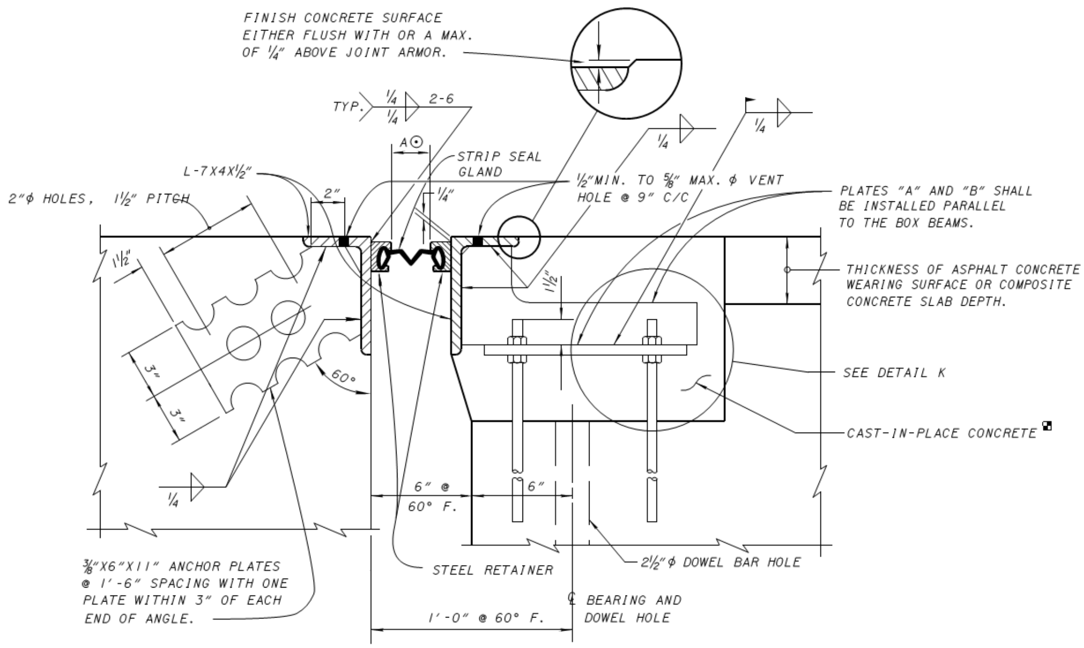


Figure C11: ODOT strip seal joint detail (concrete box beam bridge)

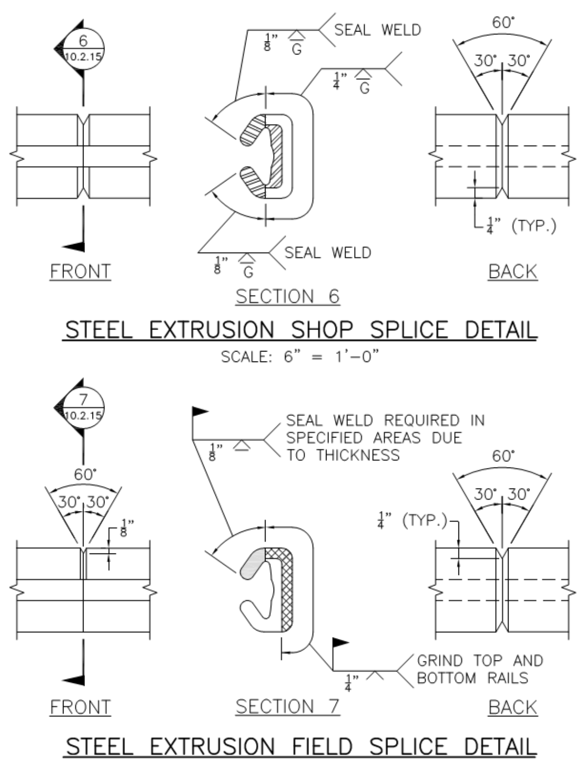


Figure C12: MassDOT steel extrusion field splice details

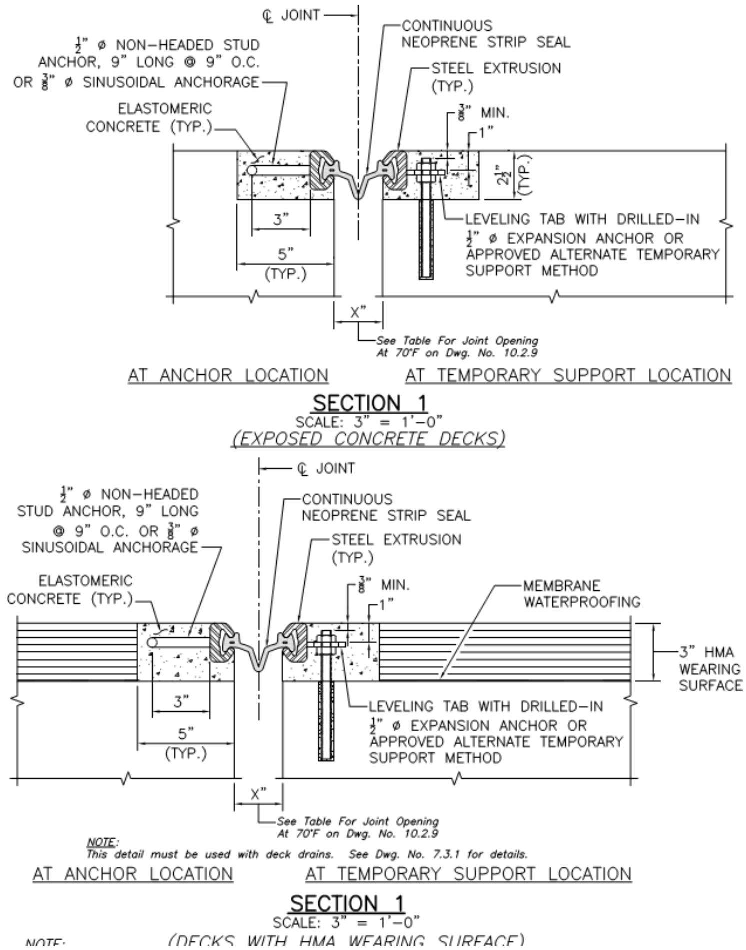


Figure C13: MassDOT strip seal joint detail

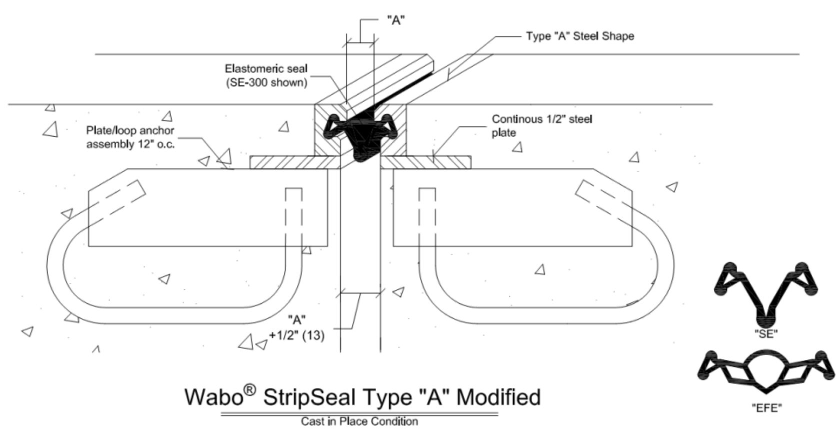


Figure C14: MassDOT Wabo StripSeal Type "A" joint detail

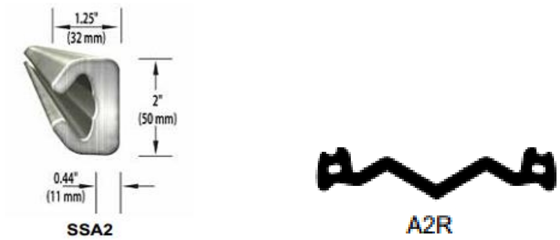


Figure C15: MassDOT D.S Brown steel extrusion (left) and strip gland (right) design

Figure C16: MassDOT D. S. Brown strip seal expansion joint detail

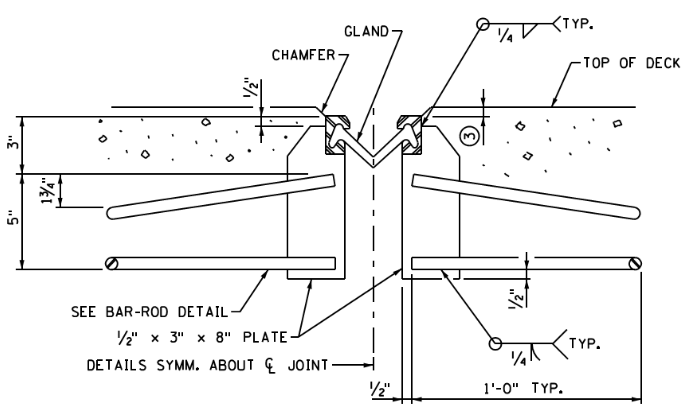


Figure C17: MnDOT strip seal joint detail

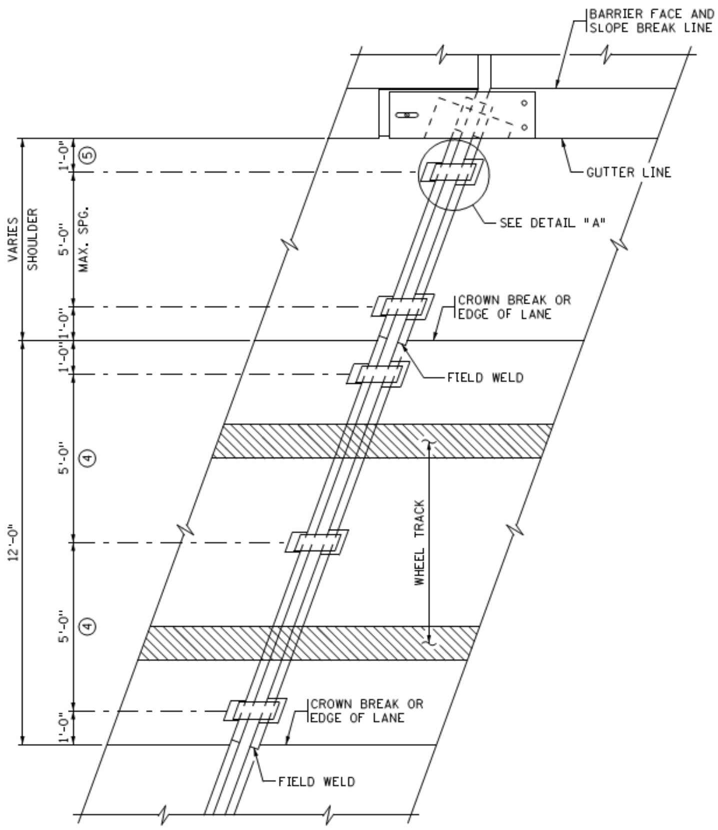


Figure C18: MnDOT plan of strip seal joint (with plow fingers)

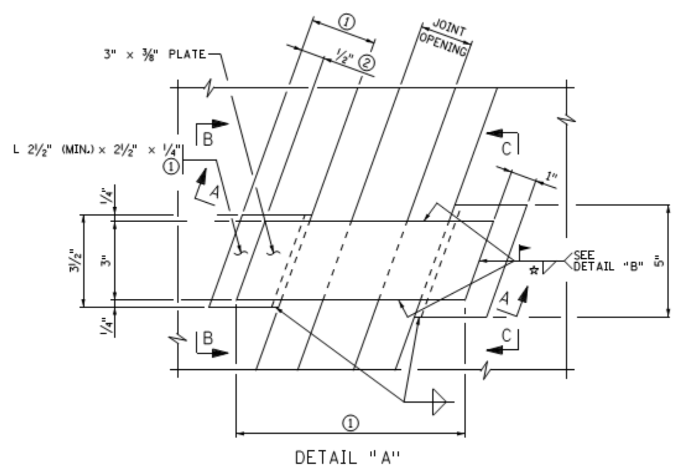


Figure C19: MnDOT plow finger detail

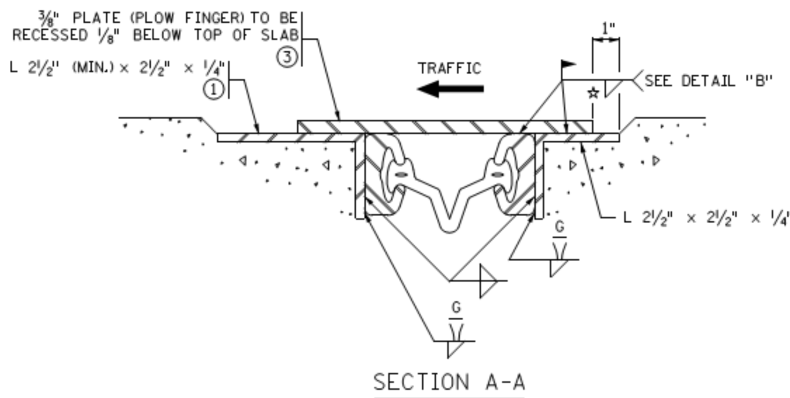


Figure C20: MnDOT strip seal joint detail at plow finger

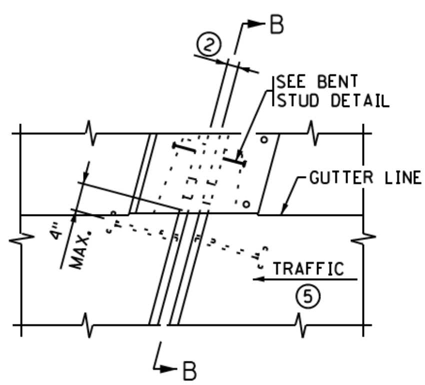


Figure C21: MnDOT plan of strip seal joint at curb-pavement interface

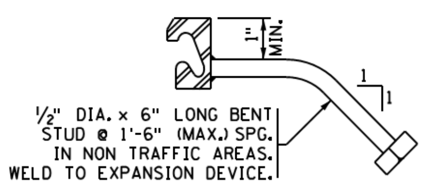


Figure C22: MnDOT steel extrusion design

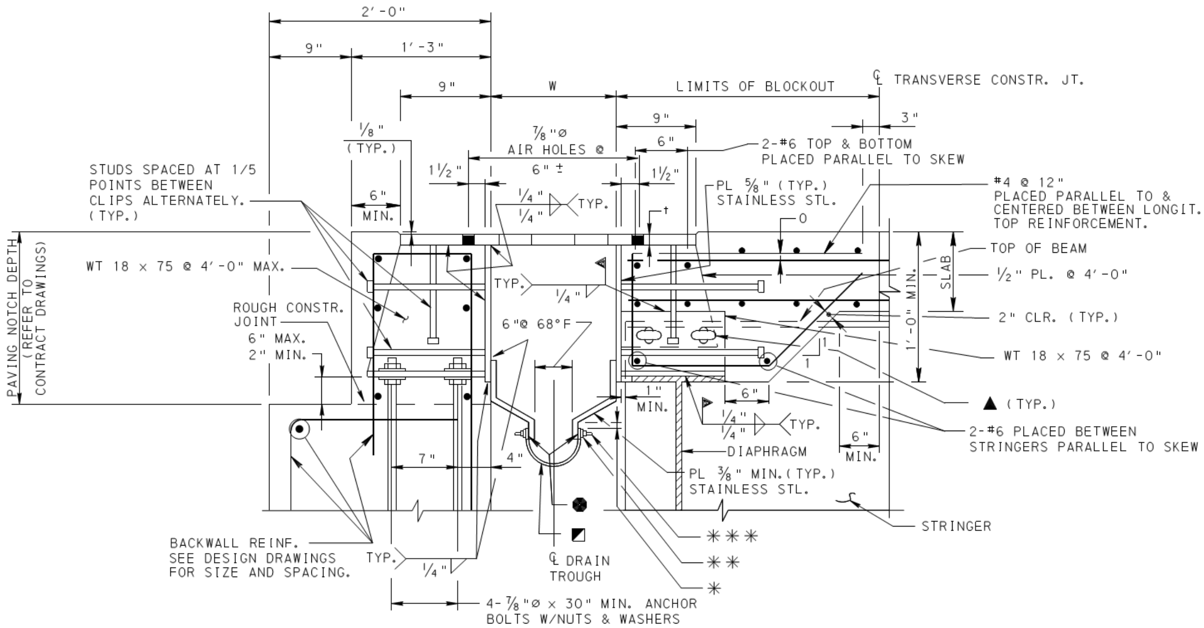


Figure C23: PennDOT tooth expansion dam detail (steel beam bridge)

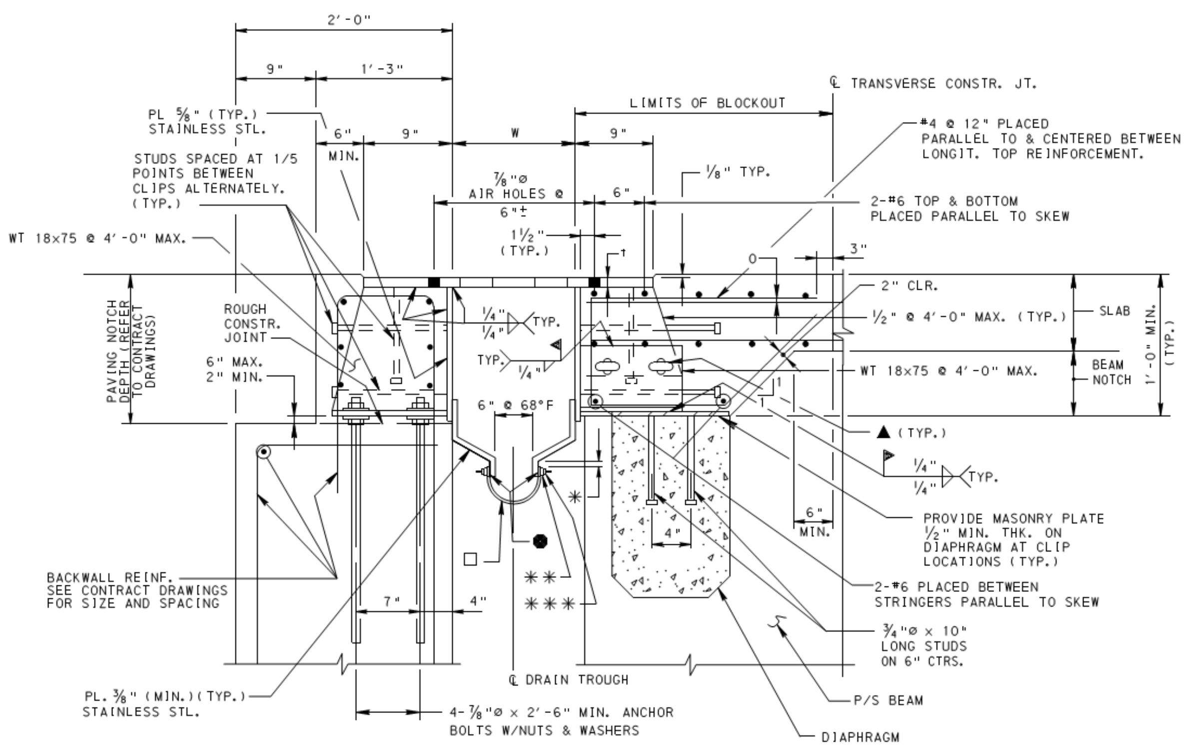


Figure C24: PennDOT tooth expansion dam detail (prestressed concrete beam bridge)

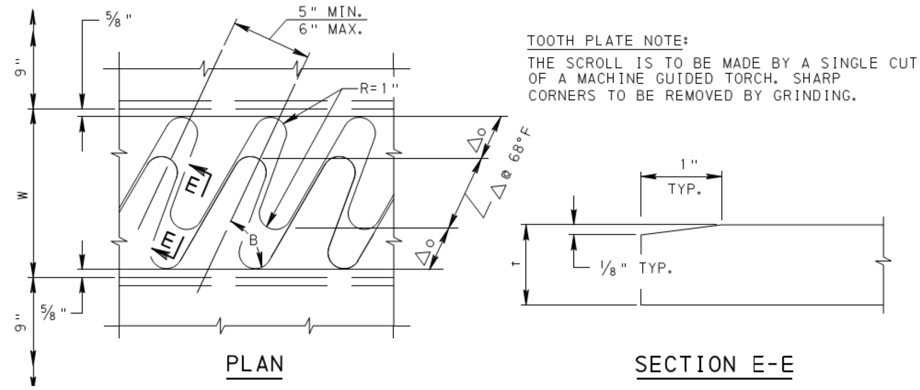


Figure C25: PennDOT steel finger design (tooth expansion dam)

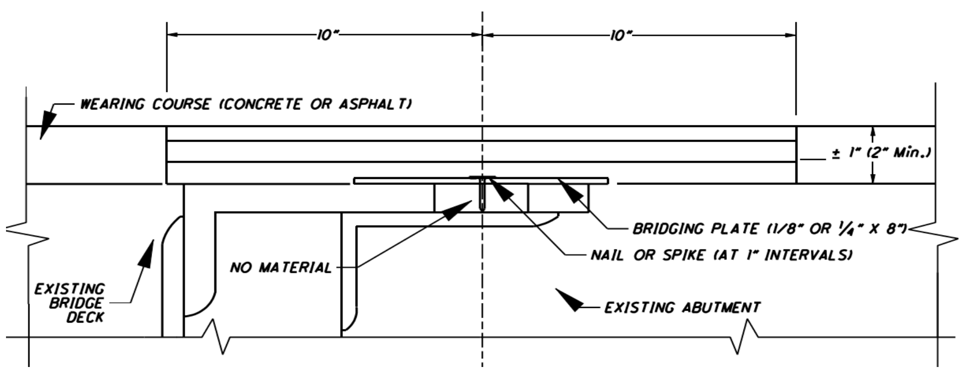


Figure C26: ODOT asphaltic plug joint detail (steel beam bridge)

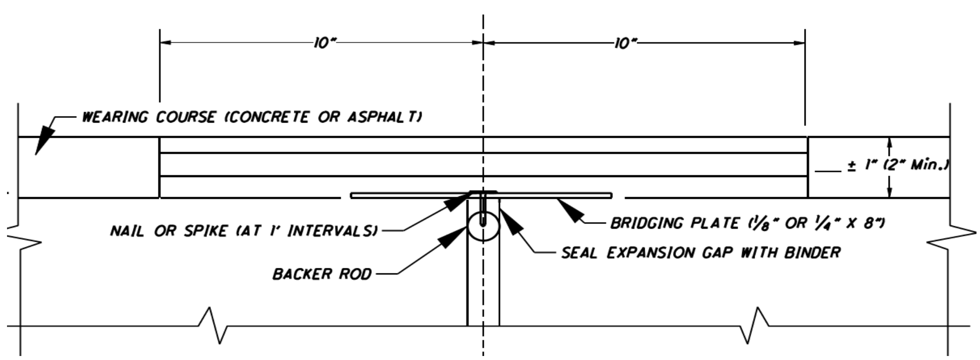


Figure C27: ODOT asphaltic plug joint detail (prestressed box beam bridge)

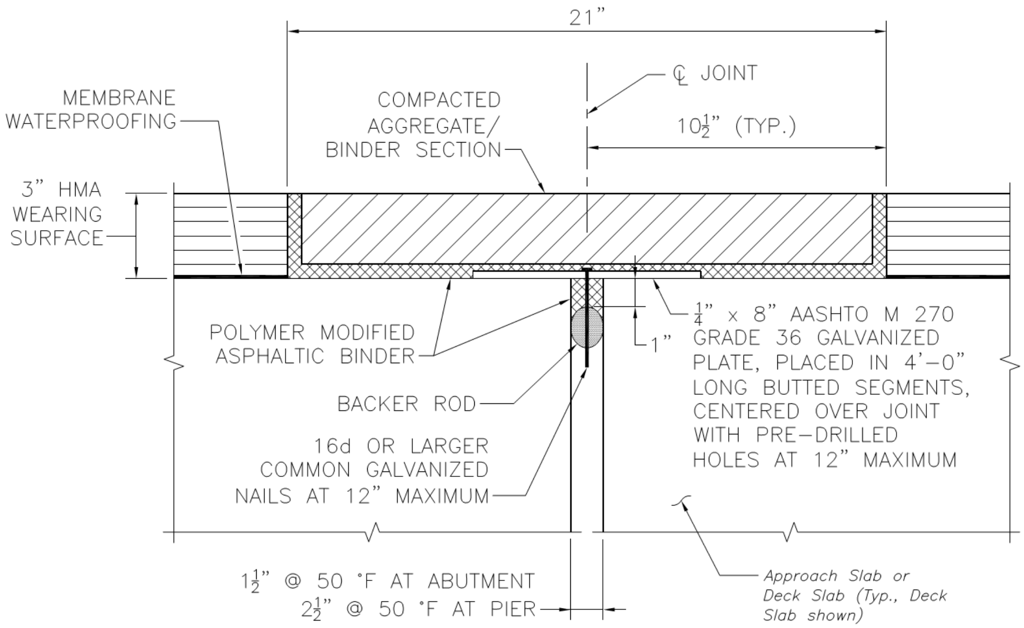


Figure C28: MassDOT asphaltic plug joint detail (with wearing course)

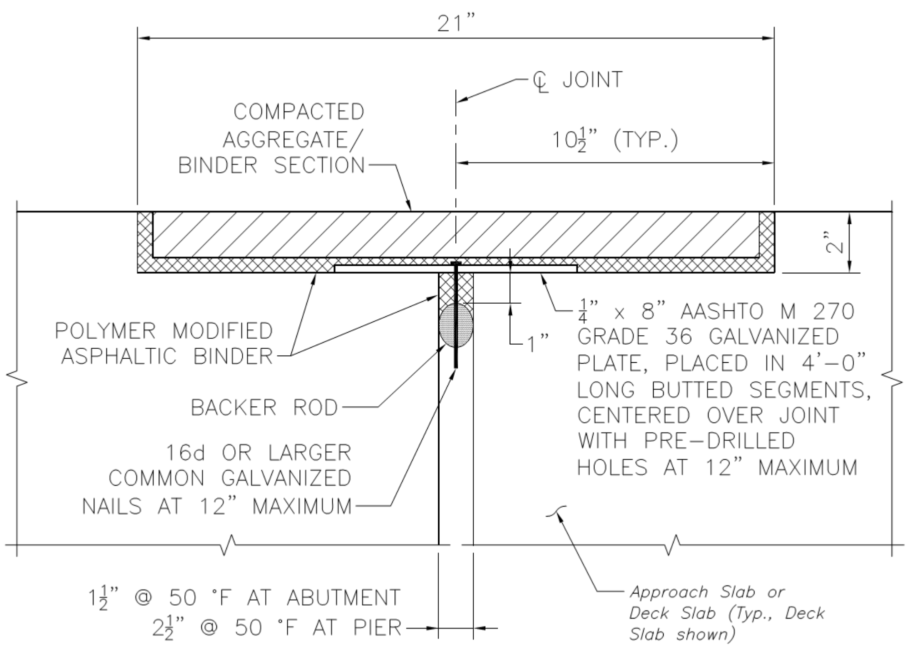


Figure C29: MassDOT asphaltic plug joint detail (without wearing course)

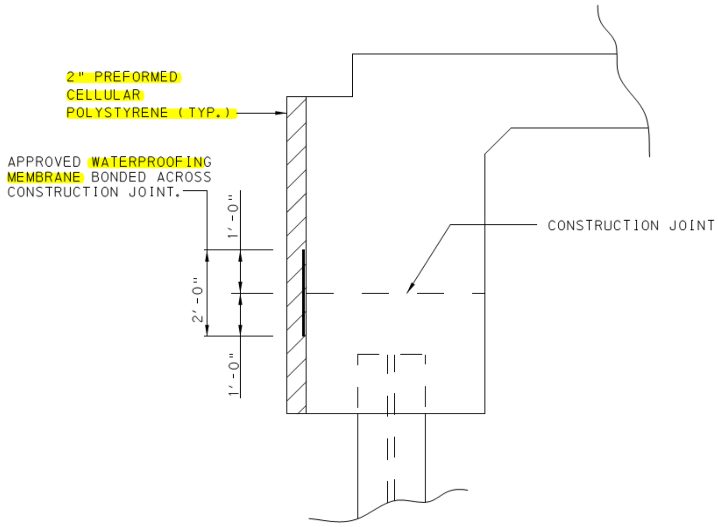


Figure C30: Integral abutment backwall waterproofing detail

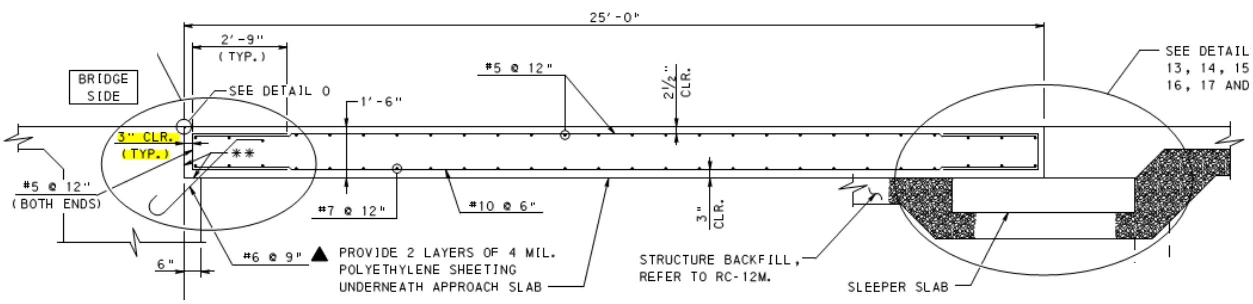


Figure C31: Waterproofing layers underneath approach slab

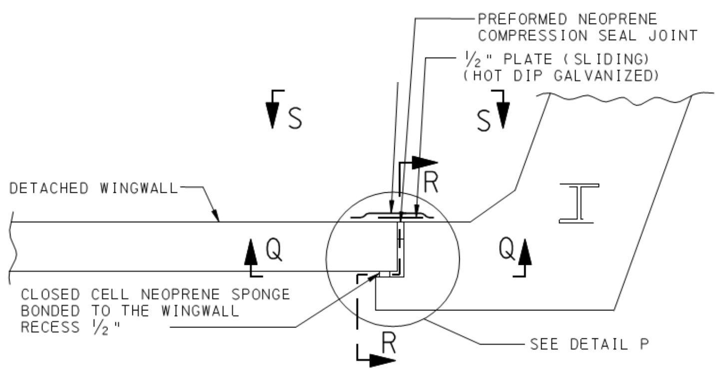


Figure C32: Partial section through detached wingwall expansion joint

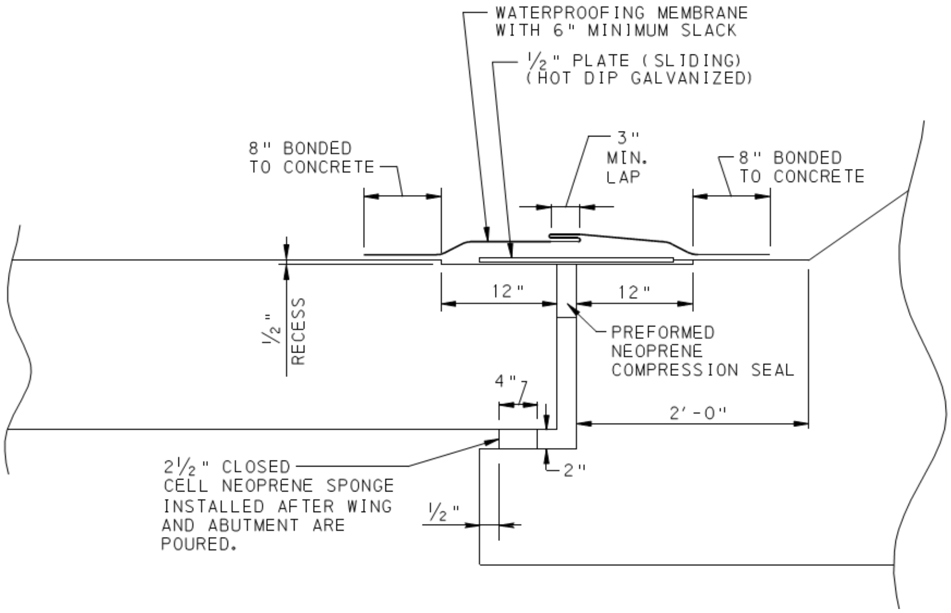


Figure C33: Detail P for figure C32

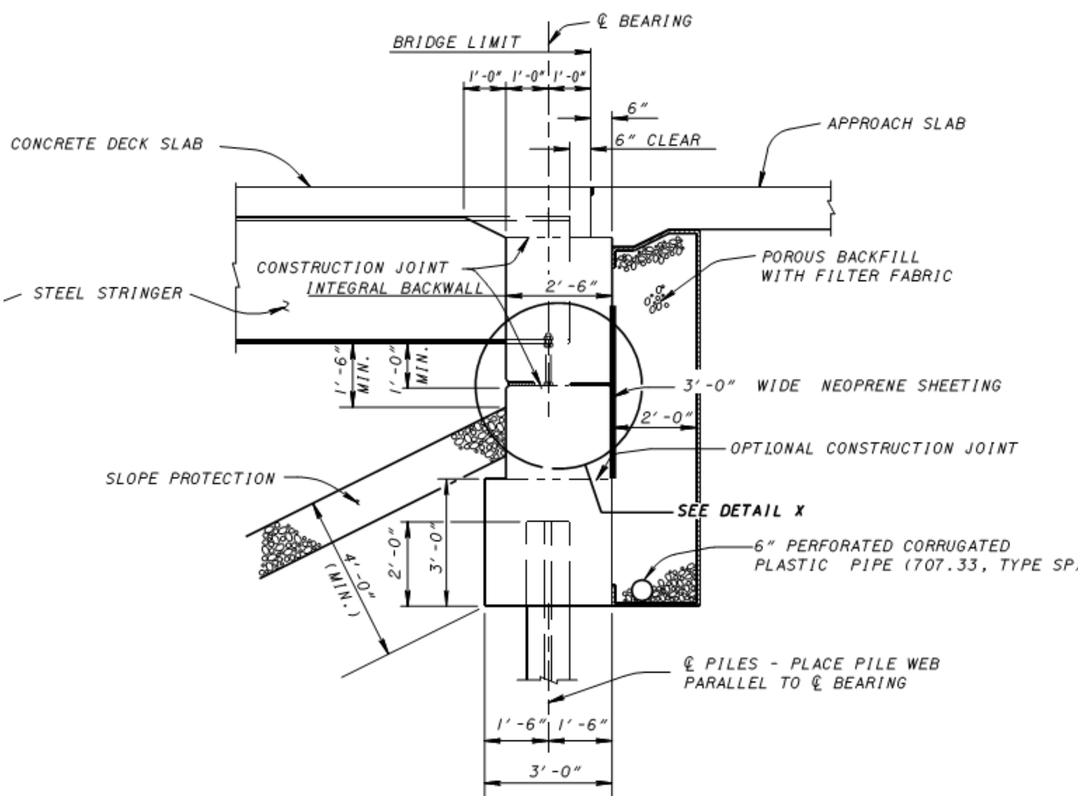


Figure C34: Section through integral abutment

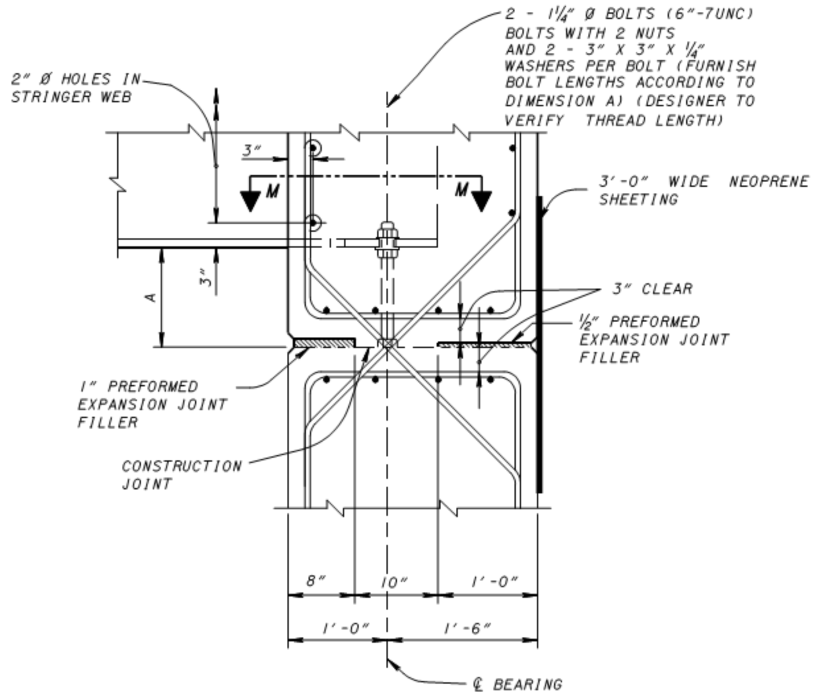


Figure C35: Detail X for figure C34

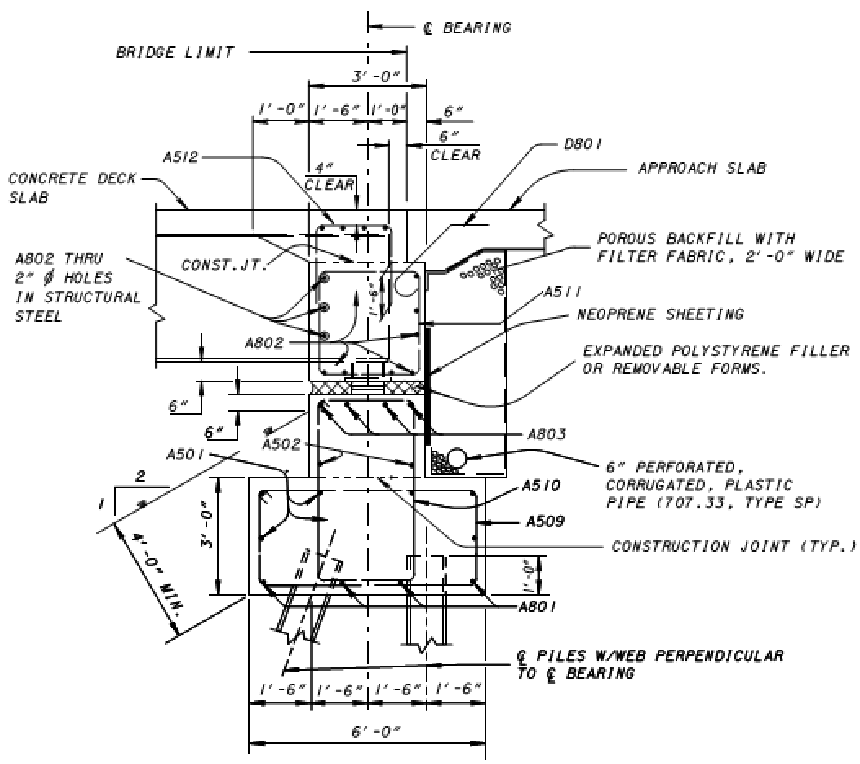


Figure C 36: Section through semi-integral abutment

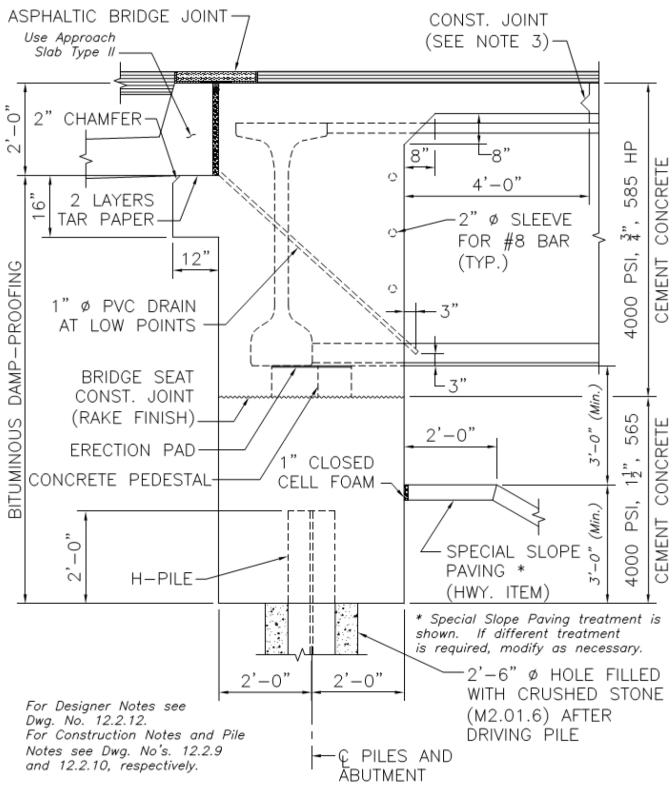


Figure C 37: Section of integral abutment

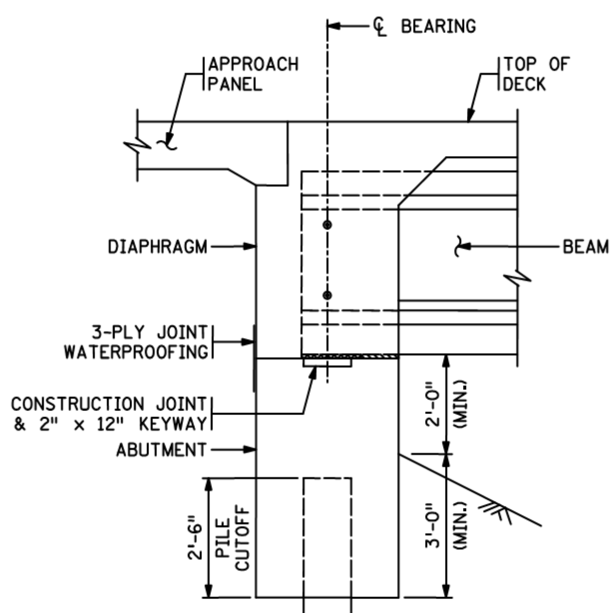


Figure C38: Section of Integral type abutment

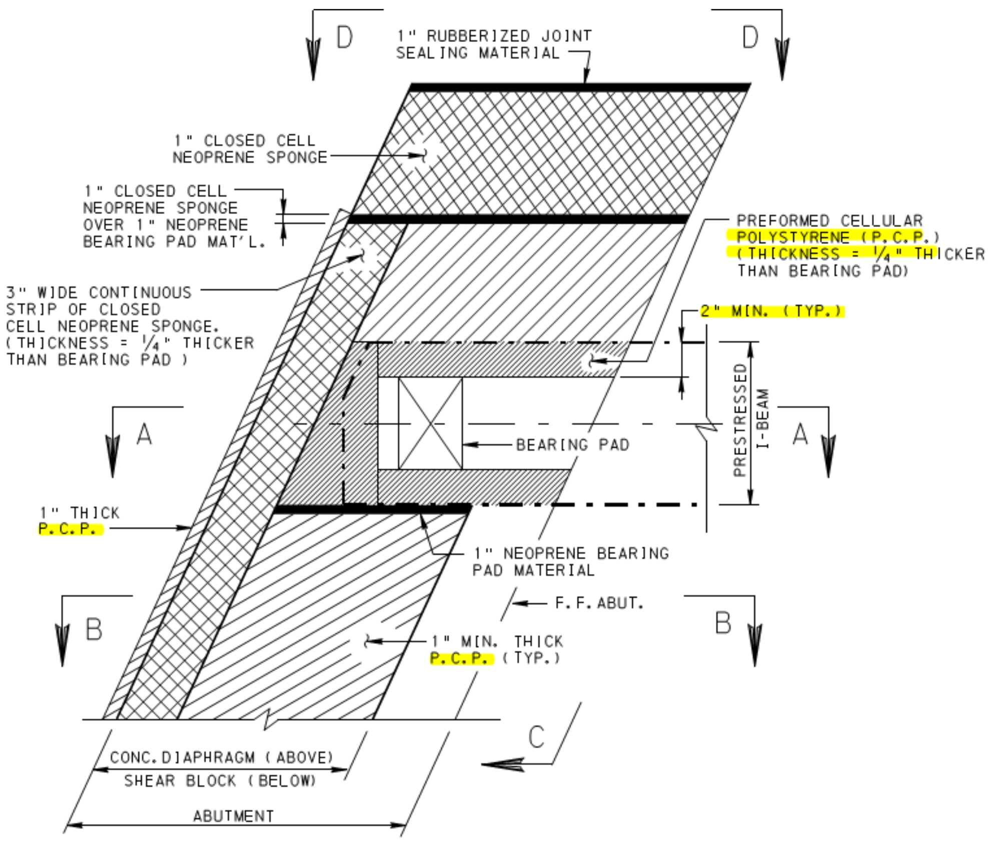


Figure C39: Plan of parapet abutment

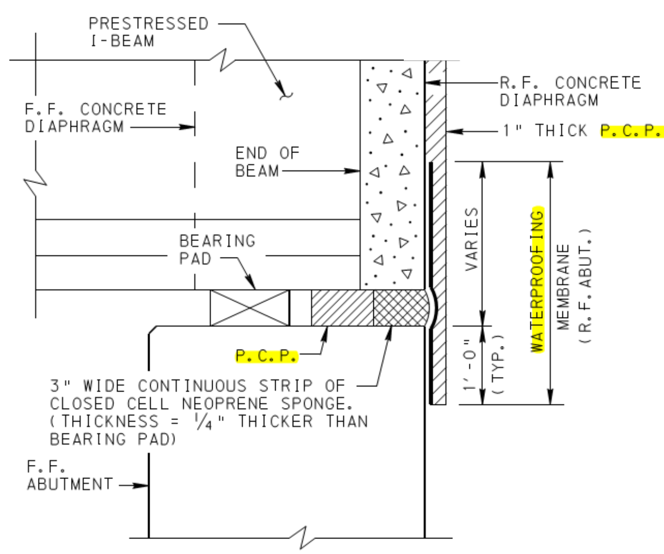


Figure C40: Section A-A in figure C39

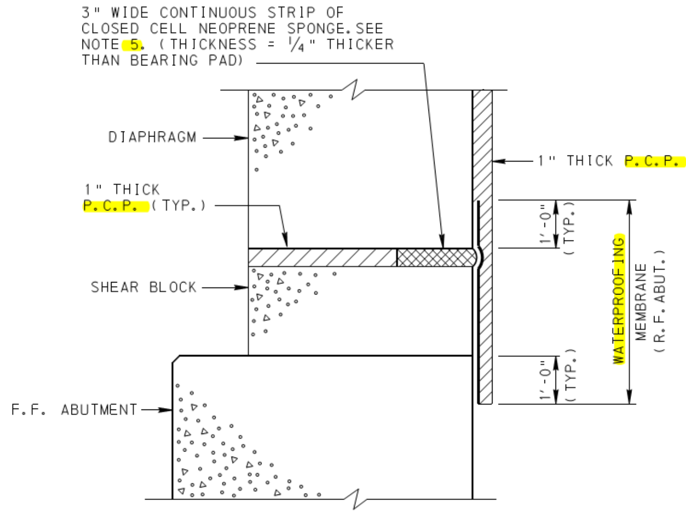


Figure C41: Section B-B in figure C39

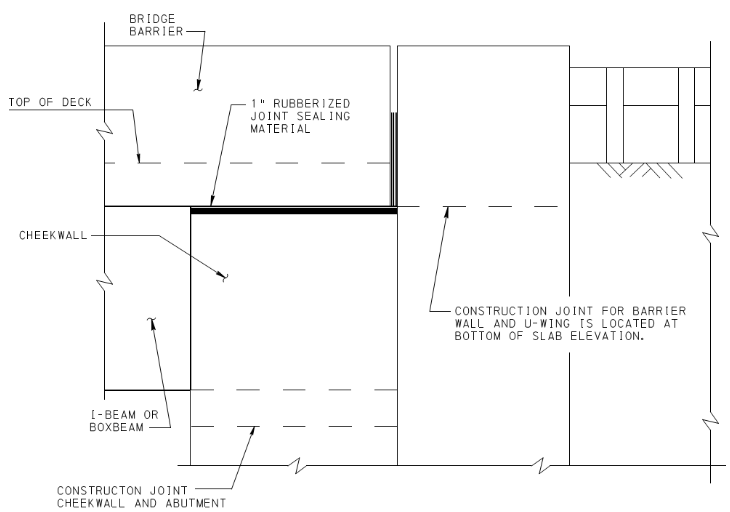


Figure C42: Section D-D in figure C39

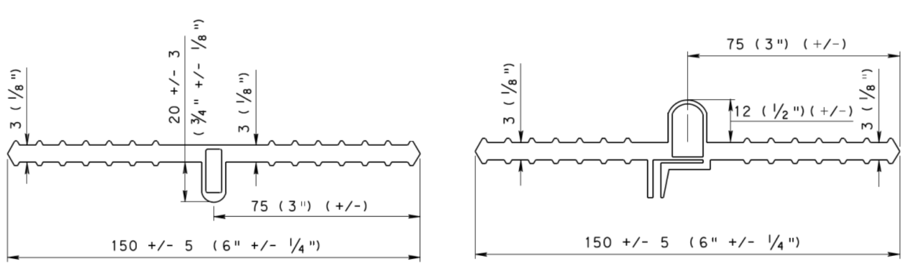


Figure C43: Waterstop designs

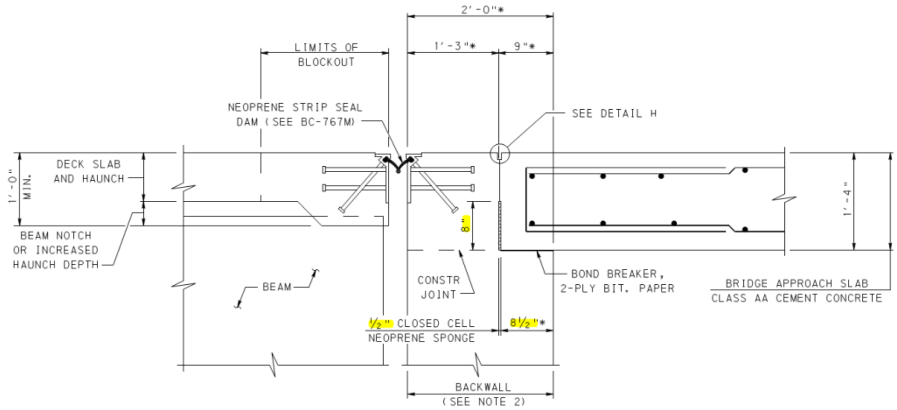


Figure C44: Approach slab with strip seal joint

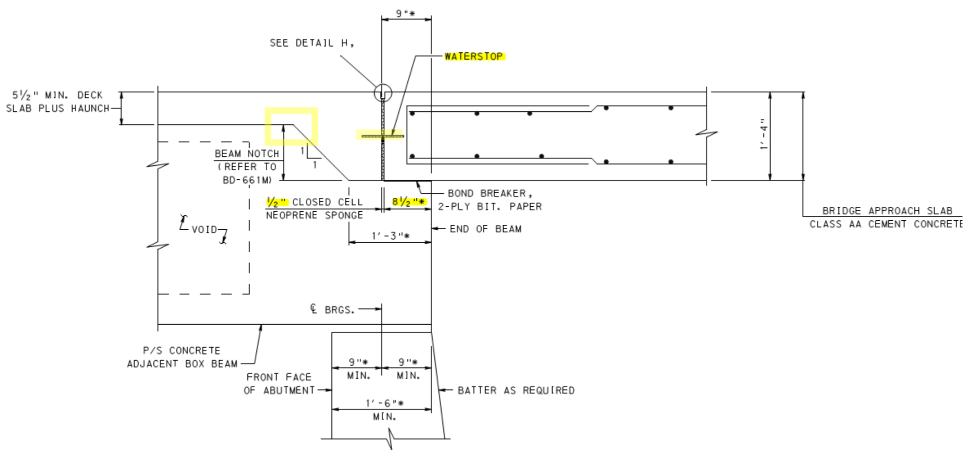


Figure C45: Approach slab with compression seal joint

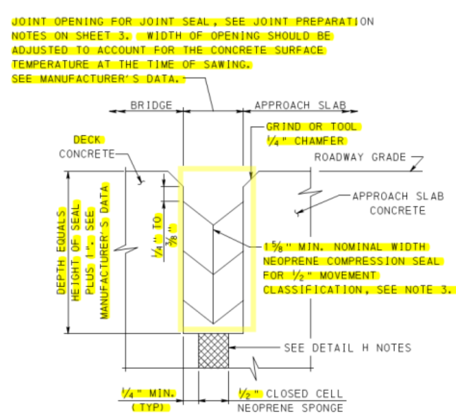


Figure C46: Detail H in figure C45

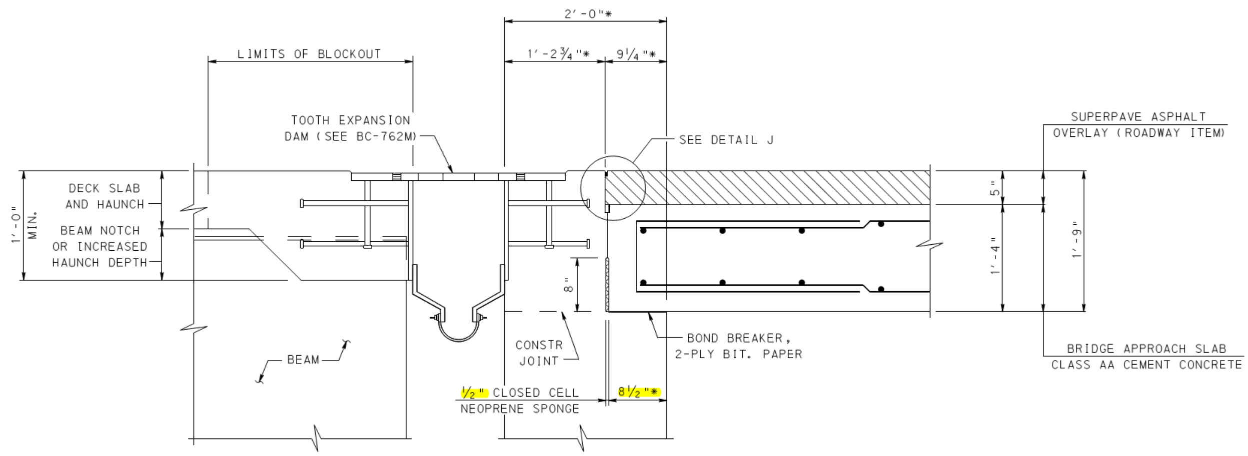


Figure C47: Approach slab with finger plate joint and an exposed drain trough

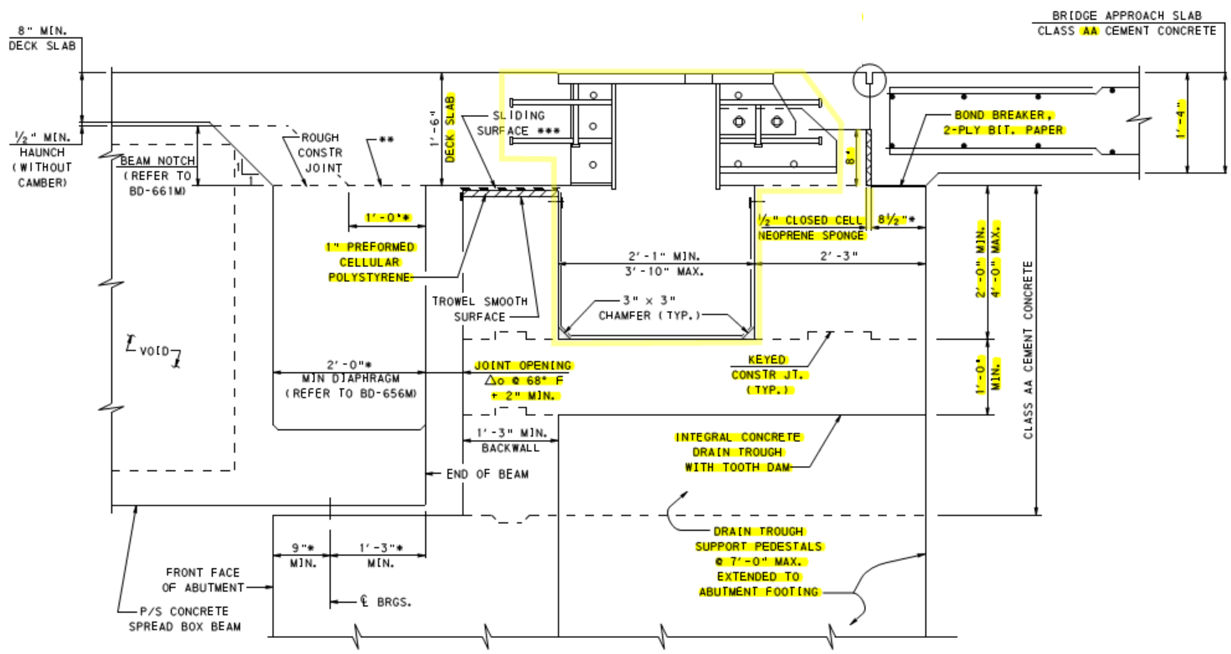


Figure C48: Approach slab with finger plate joint with an integrated drain trough

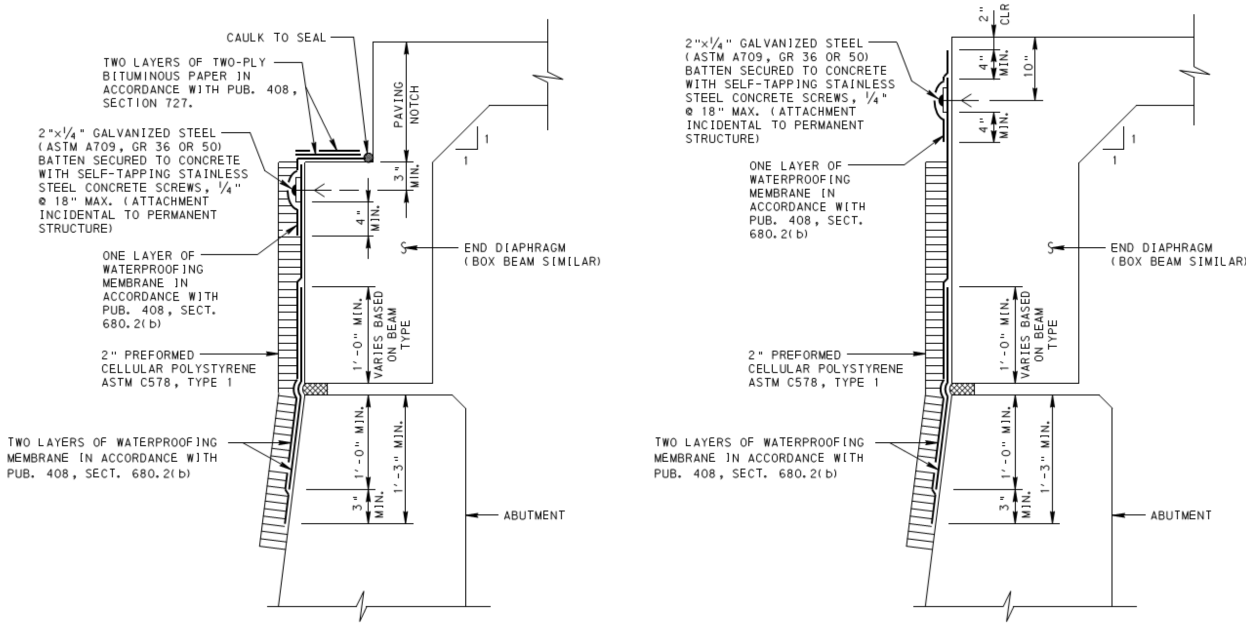


Figure C49: Waterproofing of abutment with and without paving notch

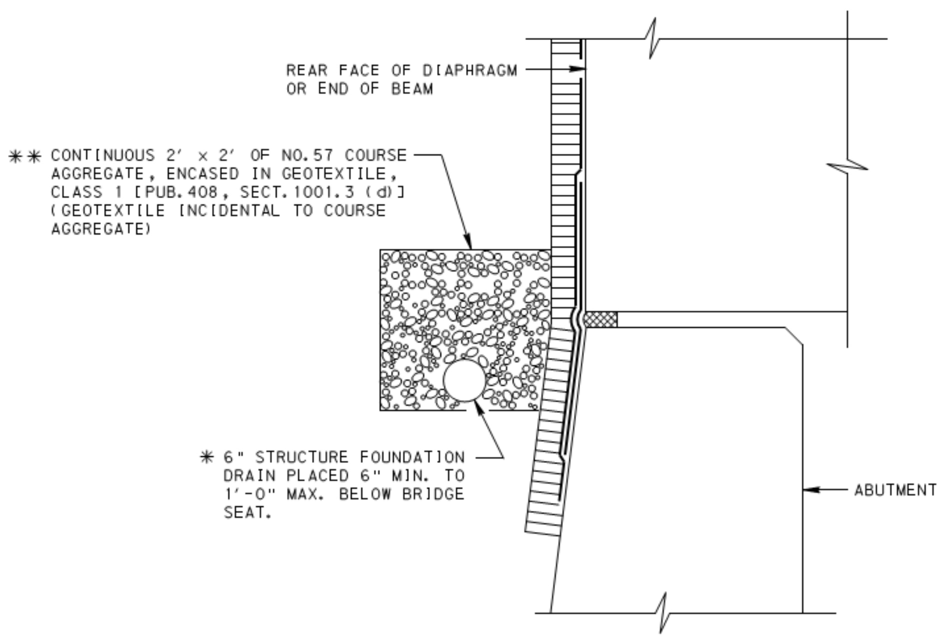


Figure C50: Drainage details at back face of abutment

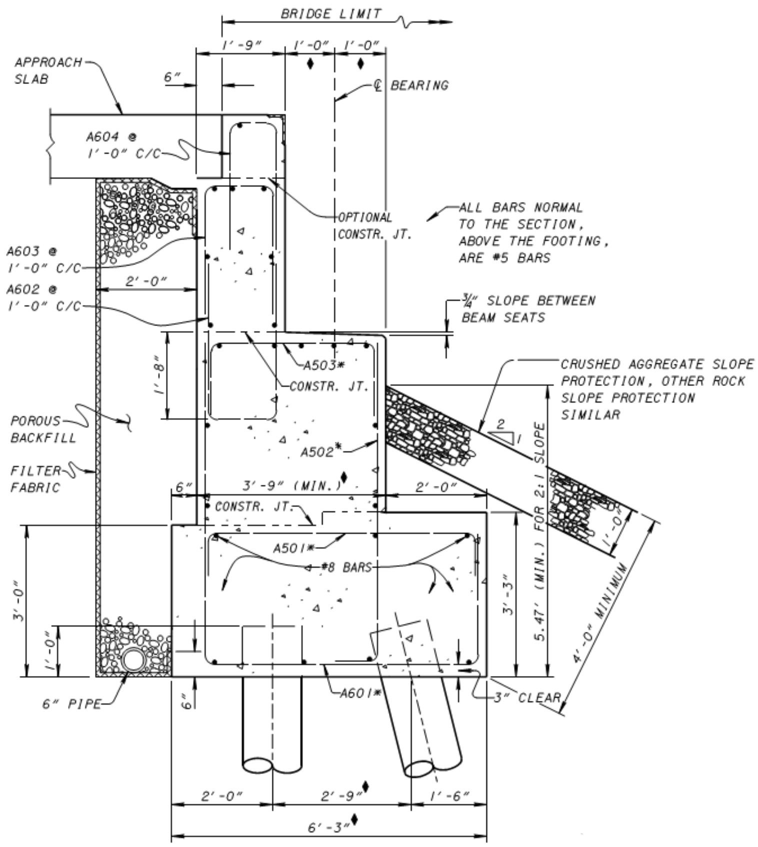


Figure C51: Waterproofing at abutment

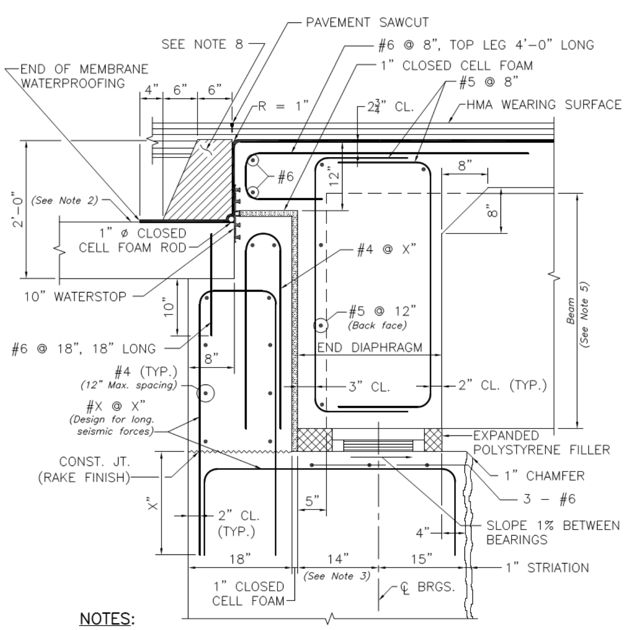


Figure C52: Waterproofing details at abutment (no expansion joint)

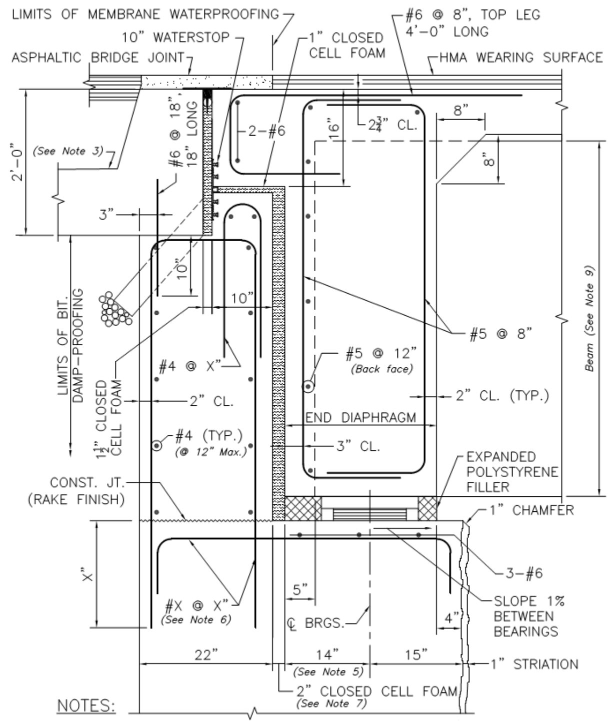


Figure C53: Waterproofing details at abutment (Asphaltic plug joint)

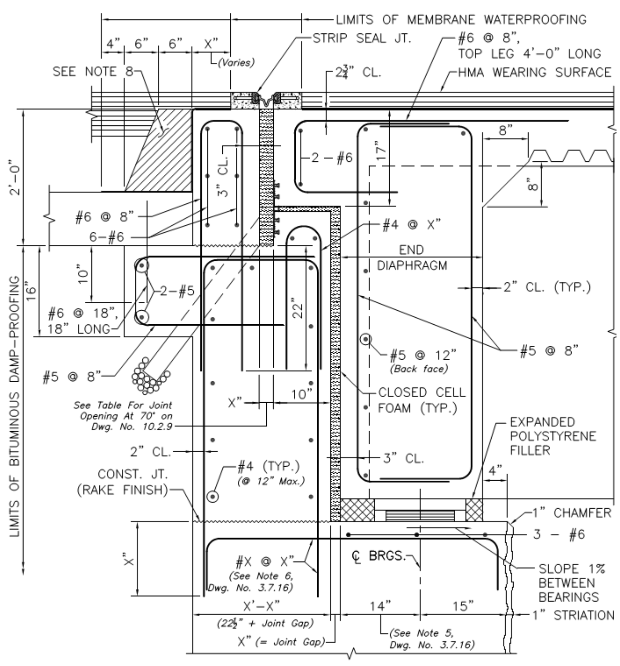


Figure C54: Waterproofing details at abutment (Strip seal joint)

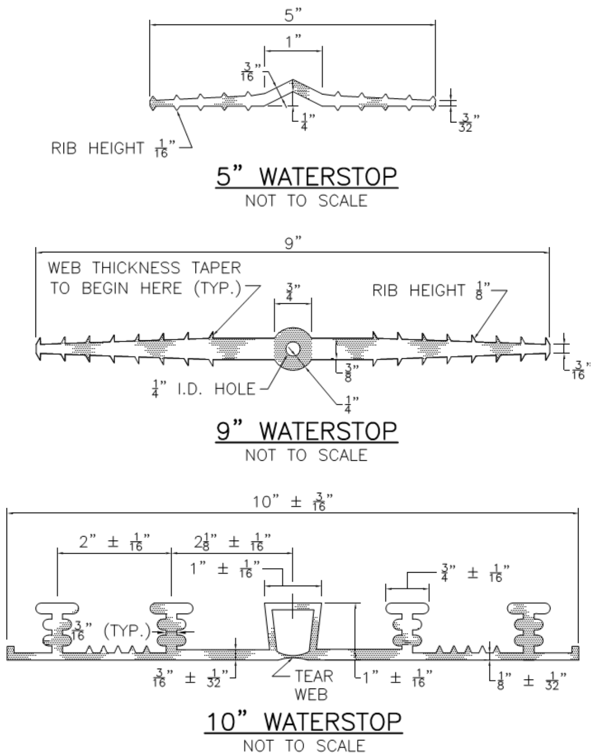


Figure C55: Waterstop details

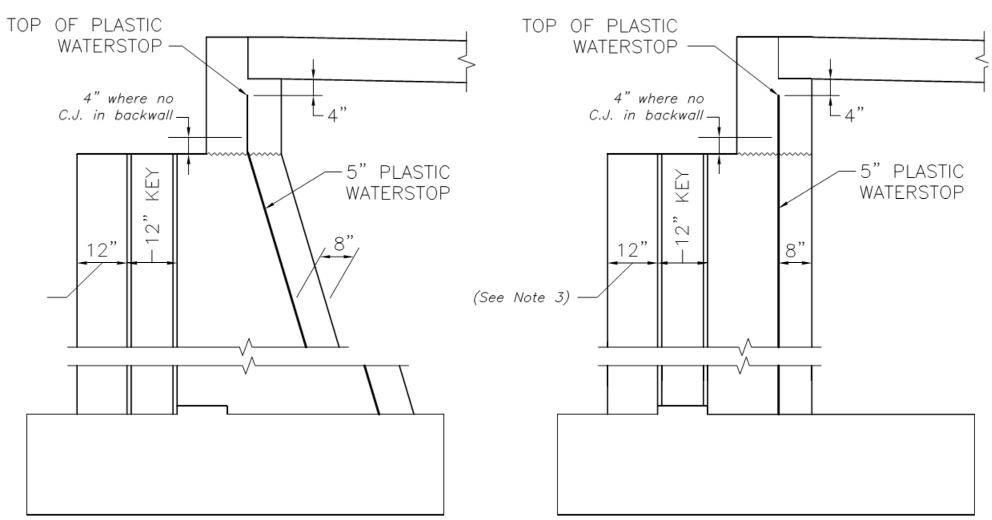


Figure C56: Waterstop through construction joint in gravity and cantilever abutments (similarly executed in wingwalls)

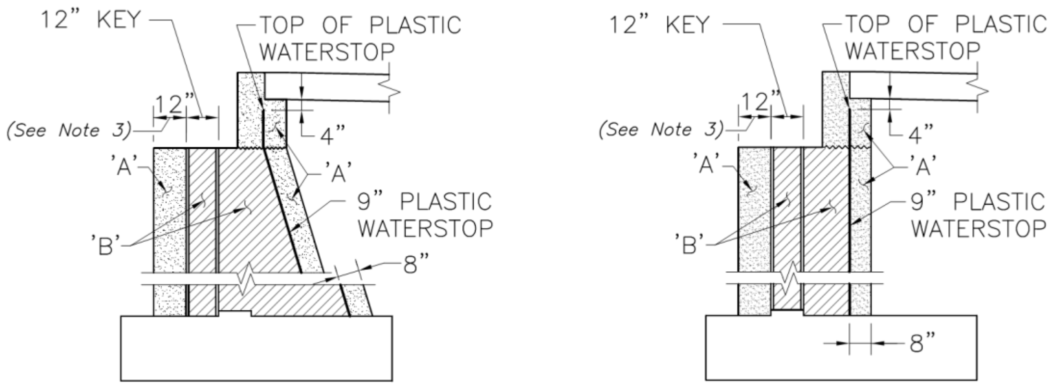


Figure C57: Waterstop through expansion joint in gravity and cantilever abutments (Similarly in wingwalls)

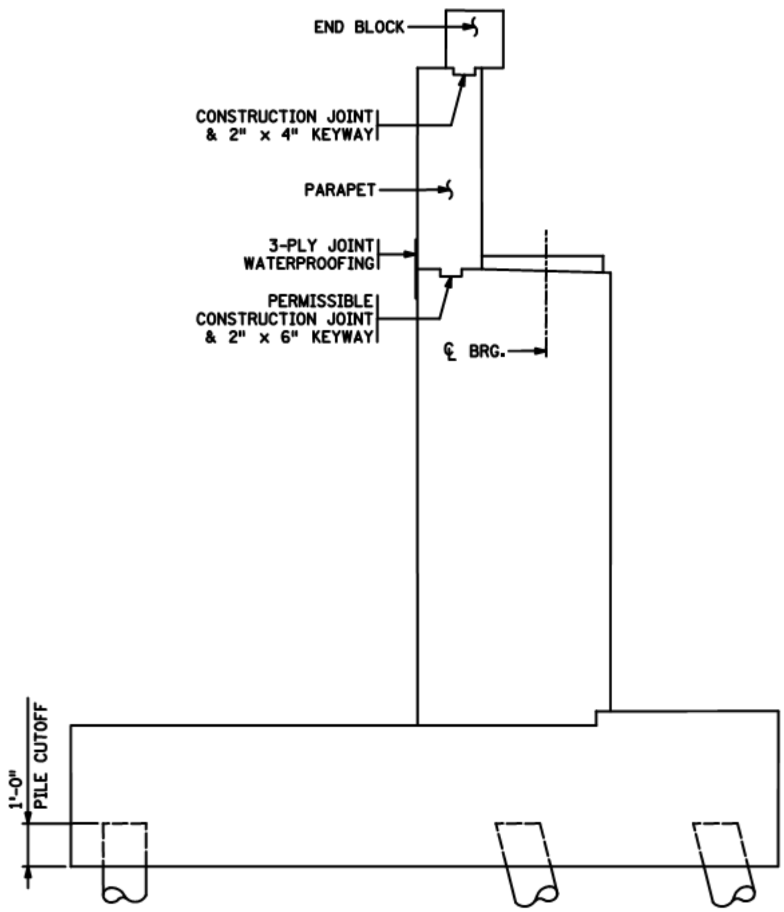


Figure C58: Waterproofing at abutment

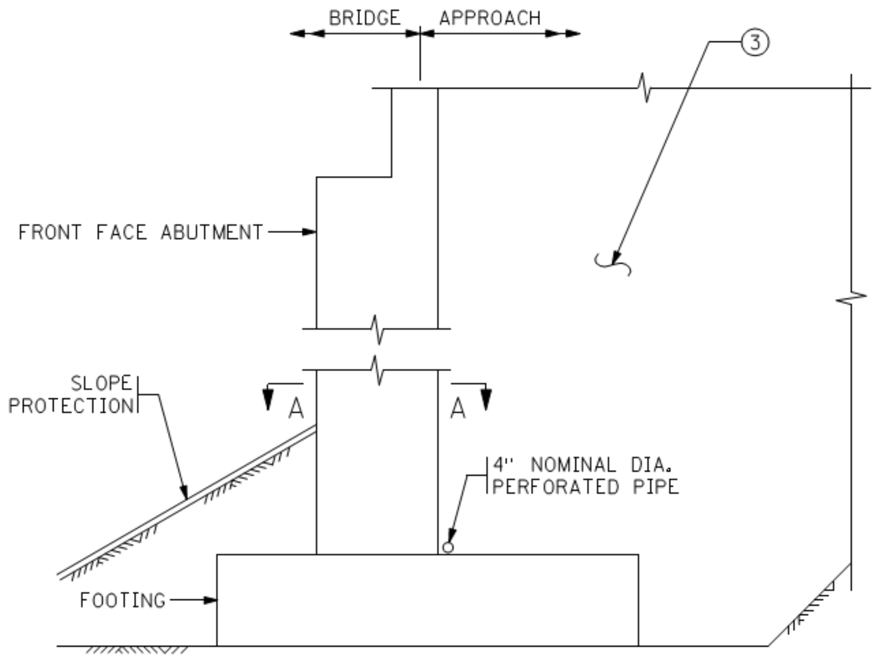


Figure C59: Section through abutment

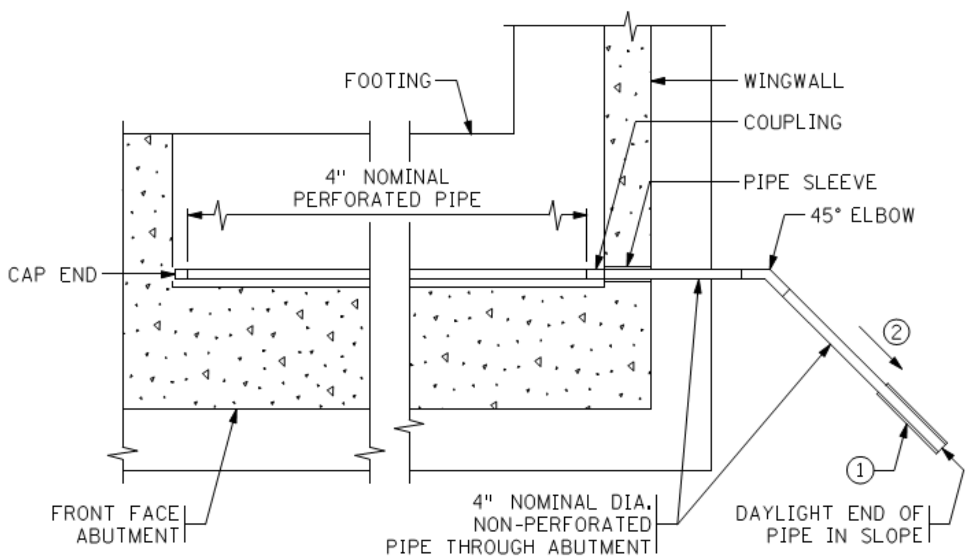


Figure C60: Section A-A in figure C59

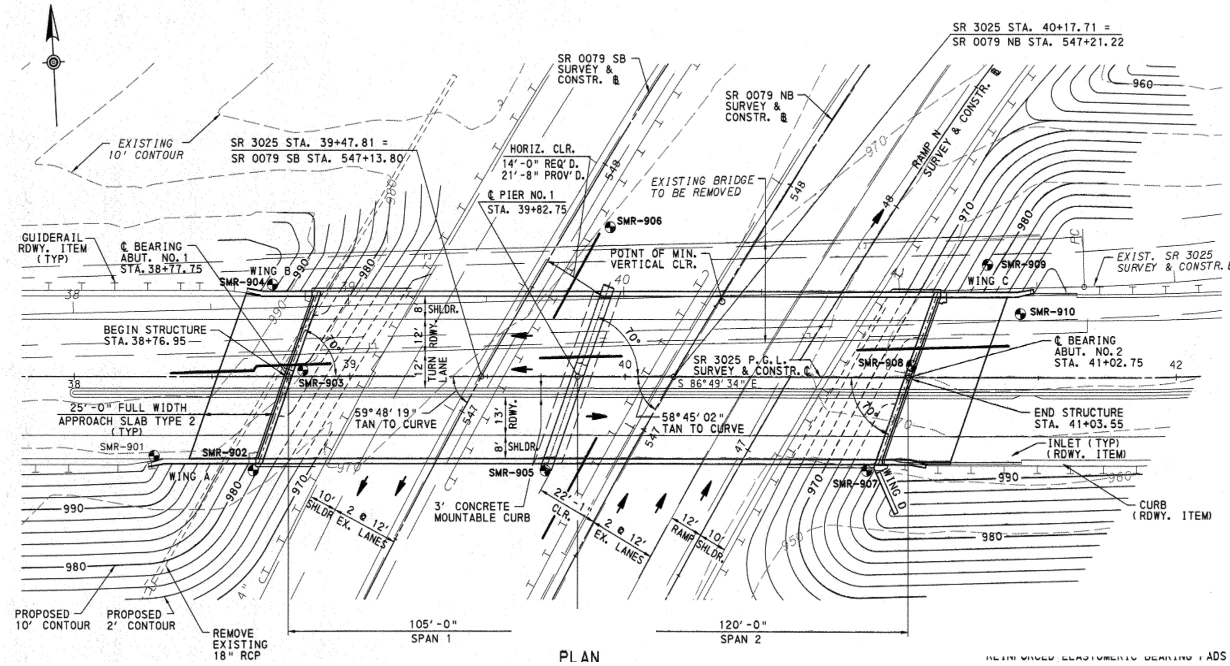


Figure C61: Plan of Little Creek Road Bridge

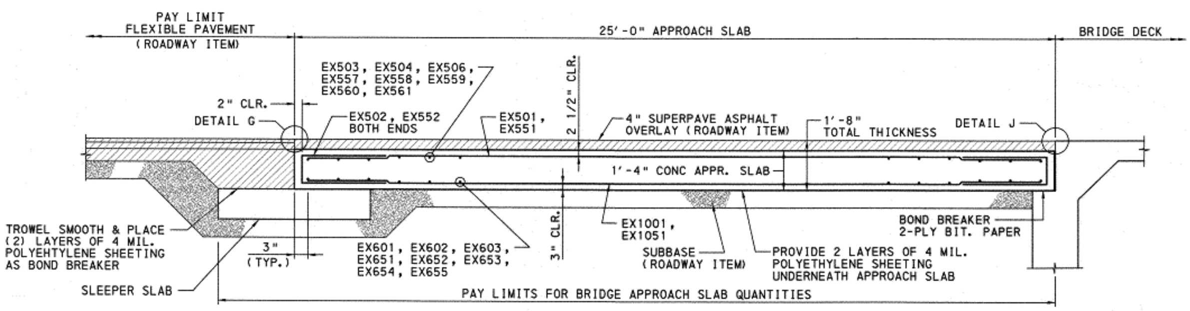


Figure C62: Section of Approach slab connected to the bridge deck

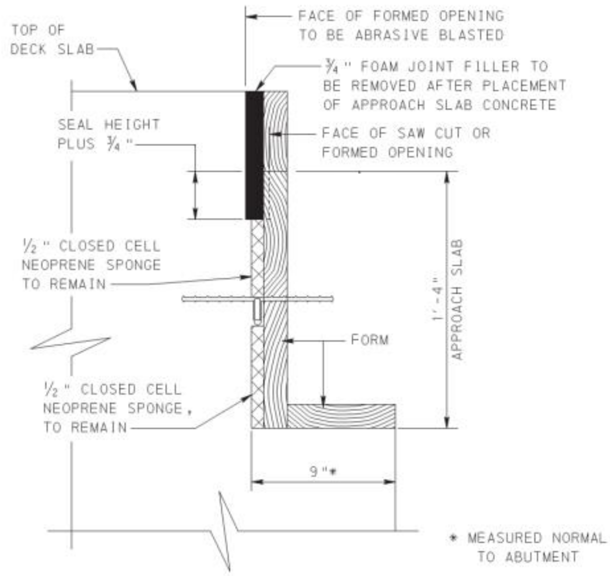


Figure C63: Waterproofing at expansion end (without approach slab in figure)

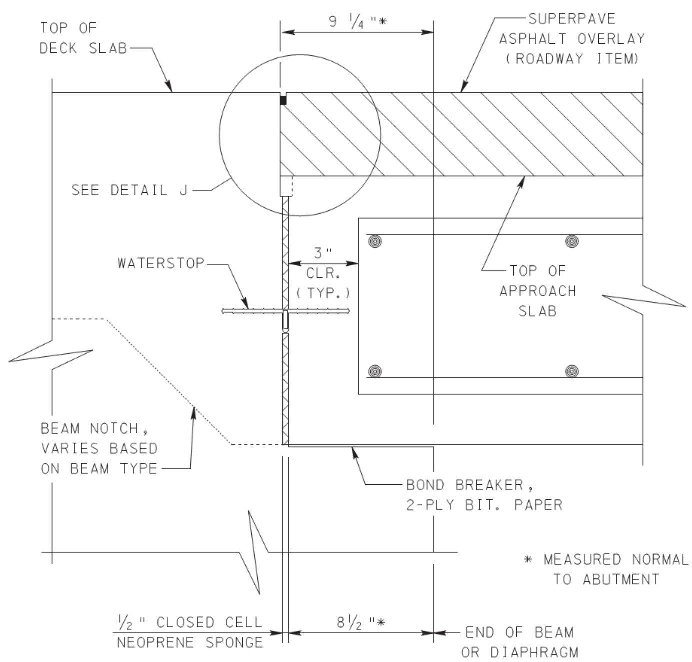


Figure C64: Waterproofing at expansion end (with approach slab in figure)

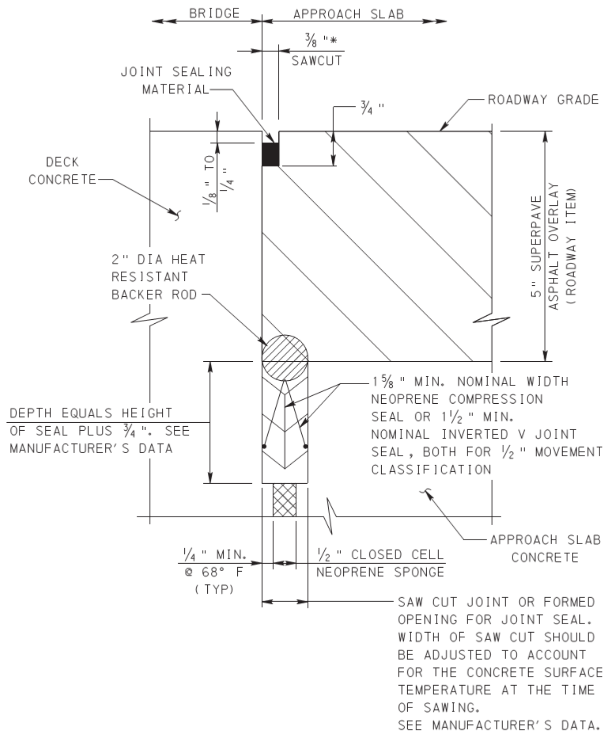


Figure C65: Detail J in figure C64

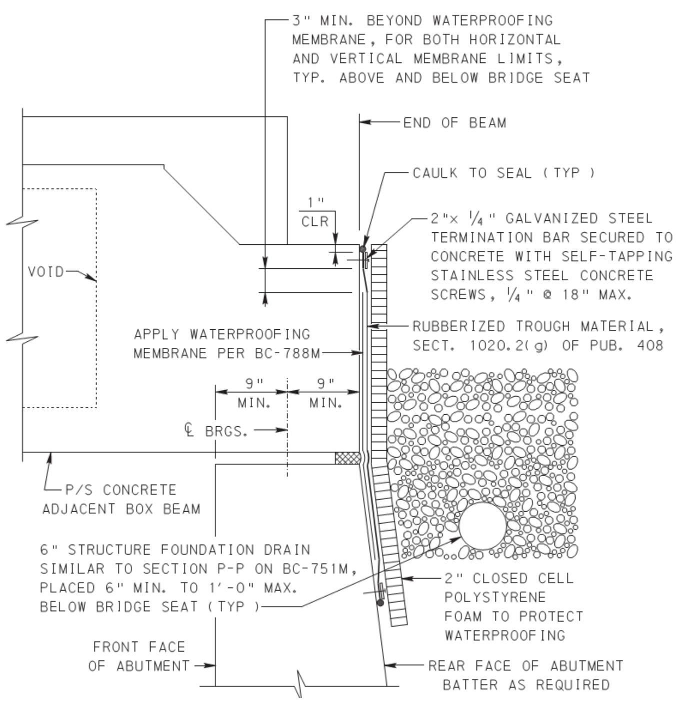


Figure C66: Waterproofing details at the substructure-superstructure interface

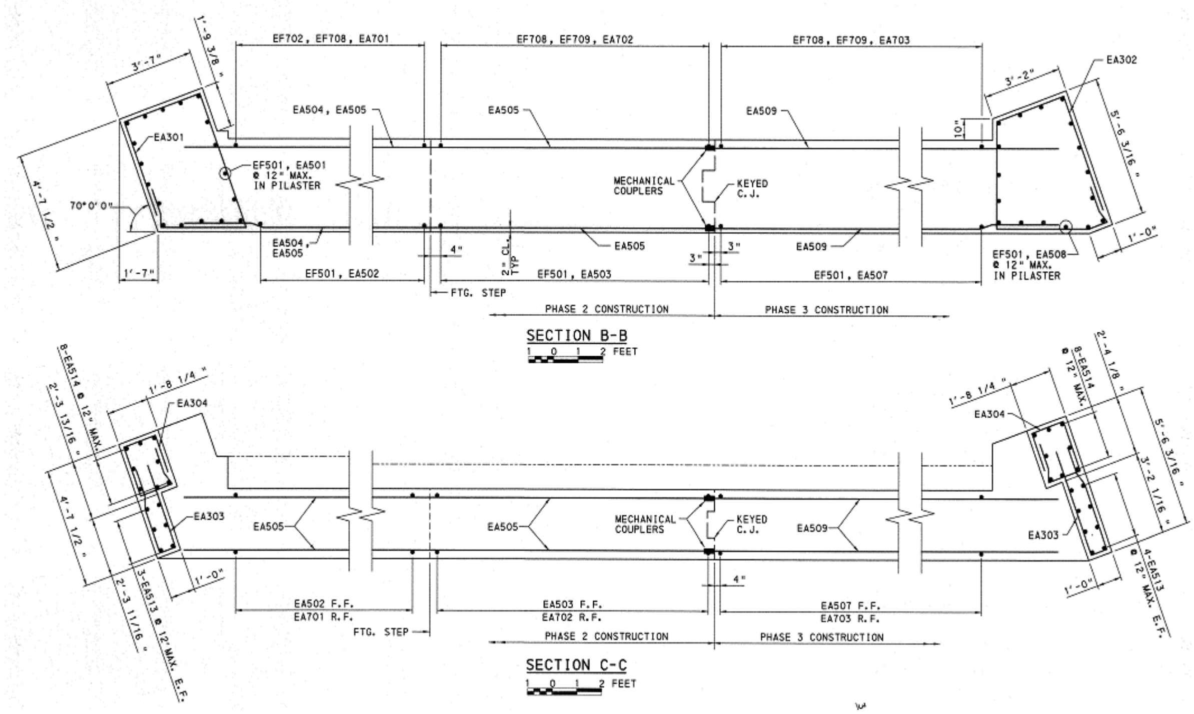


Figure C67: Section of abutment

Figure C68: Cracking and erosion of edges in contact with sealant

Figure C69: Damaged Silicone sealant seal

Figure C70: Close-up of damaged seal in figure C68

Figure C71: Interface of bridge deck and approach slab

Figure C72: Leakage at interface of abutment backwall and beam

Figure C73: Leakage at interface of abutment backwall and beam

Figure C74: Leakage at edge of abutment

Figure C75: Detour of part of discharge into joint

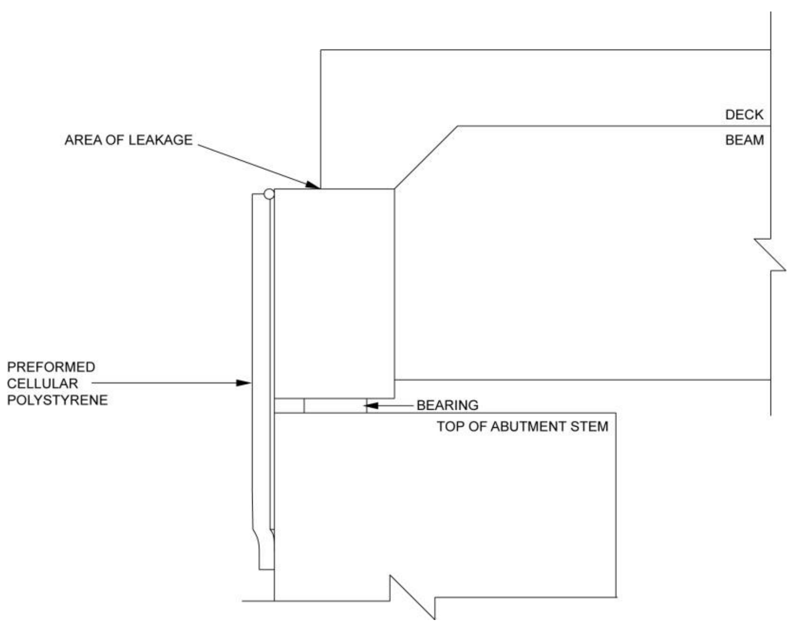


Figure C 76: Depiction of waterproofing membrane inadequacy at abutment-expansion joint interface

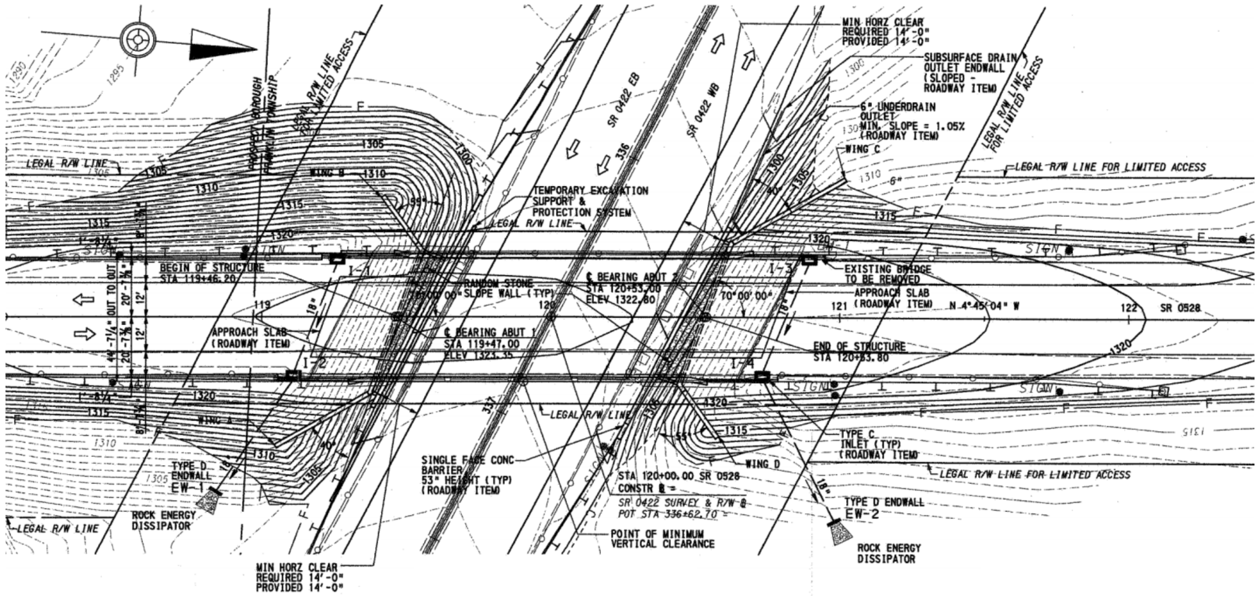


Figure C77: of Prospect #1 Bridge

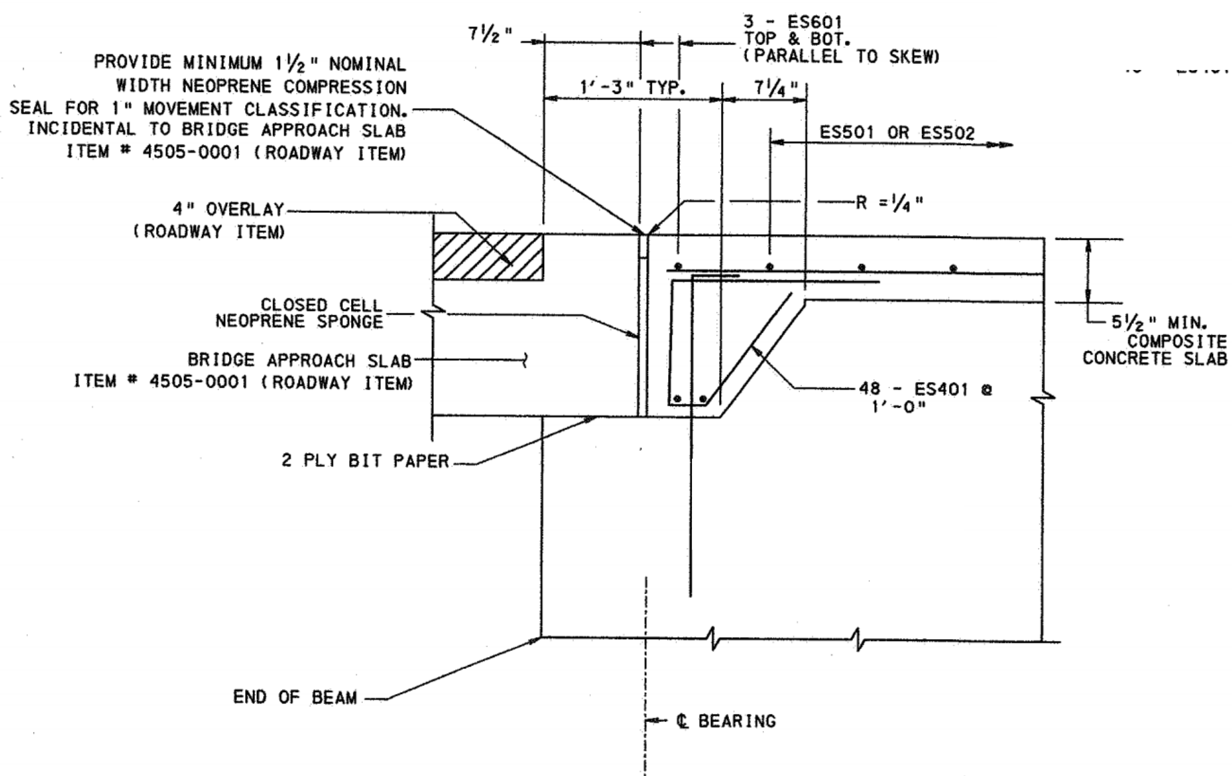


Figure C78: Detail of Compression seal joint

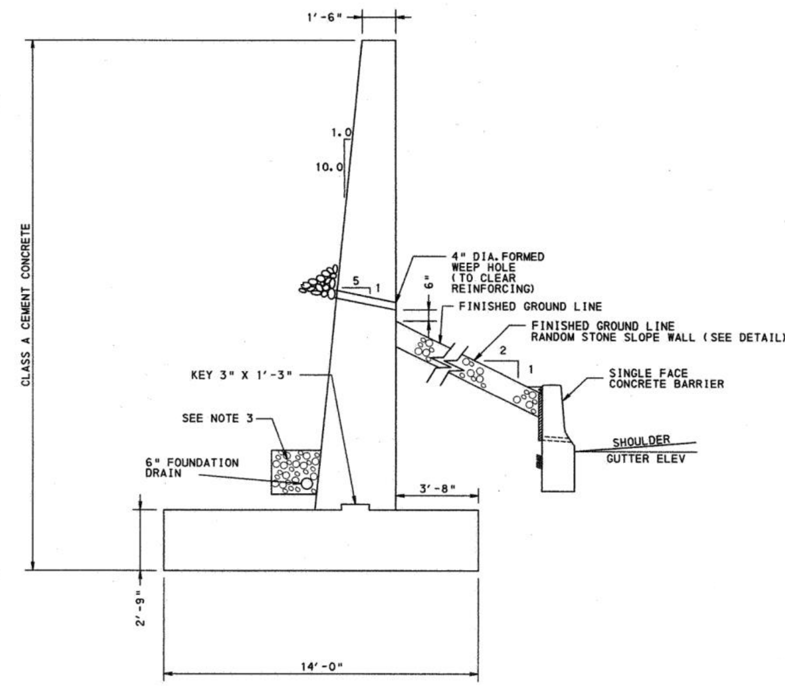


Figure C79: Cross-section of retaining wall in abutment

Figure C80: Moderate debris accumulation in expansion joint

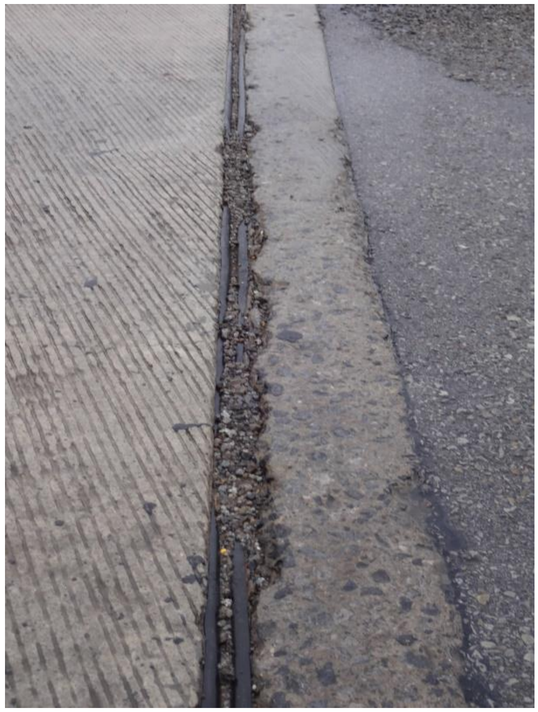


Figure C81: Severe debris accumulation in expansion joint

Figure C82: Maintenance works overlapping on expansion joint and deterioration of concrete edges

Figure C83: Water staining on abutment

Figure C84: Severe water staining on edge of abutment wall

Figure C85: Water staining on top and bottom of back wall on abutment seat

Figure C86: Water ponding at the edge of the deck near the expansion joint

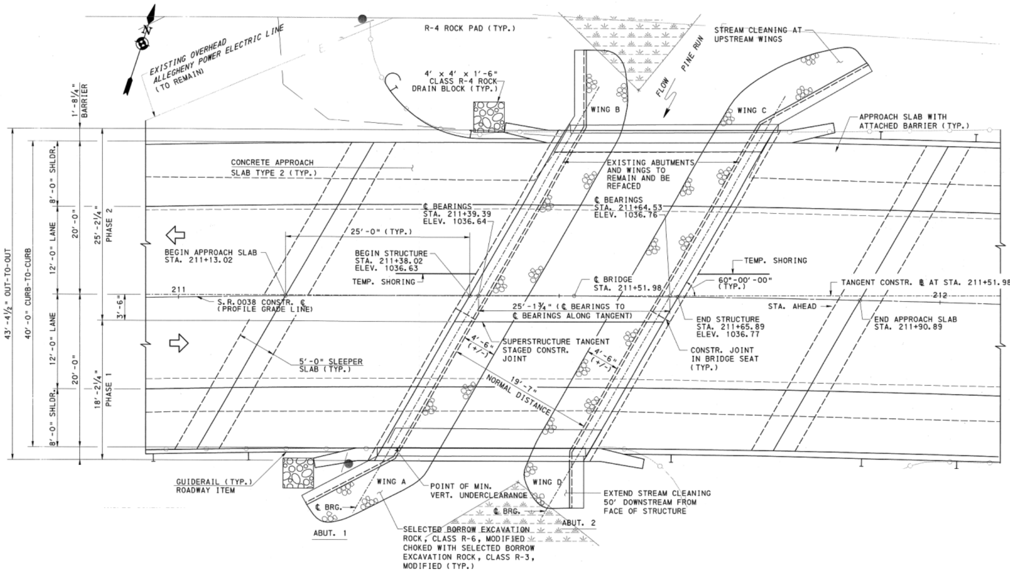


Figure C87: Plan of SW of Boydstown Bridge

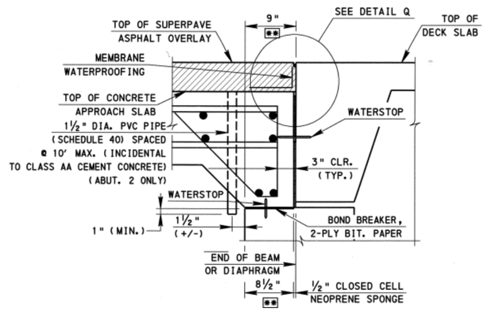


Figure C88: Details of Expansion Joint

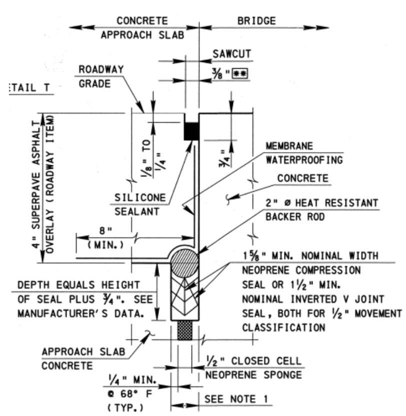


Figure C89: Detail Q in figure C88

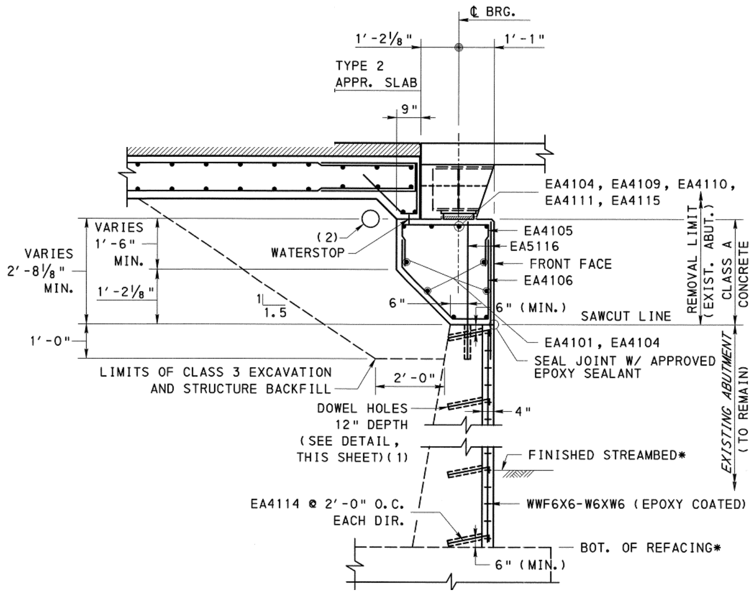


Figure C90: Section of Retaining wall in abutment

Figure C91: Minor deterioration of edges along joint

Figure C92: Leakage in bridge abutment seat

Figure C93: Leakage in cracks propagating from the abutment stem and header interface

Figure C94: Leakage through cracks with efflorescence

Figure C95: Silt deposition with lack of flow of water along deck edge

Figure C96: Silt deposition in weep hole

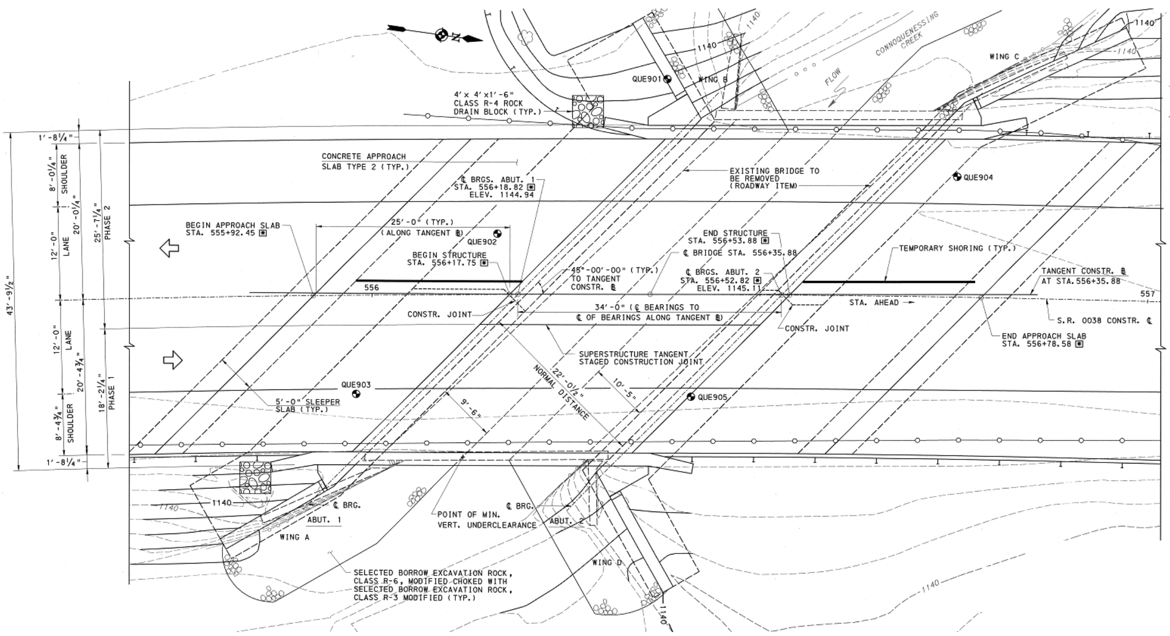


Figure C97: Plan of Little Connoquenessing Bridge

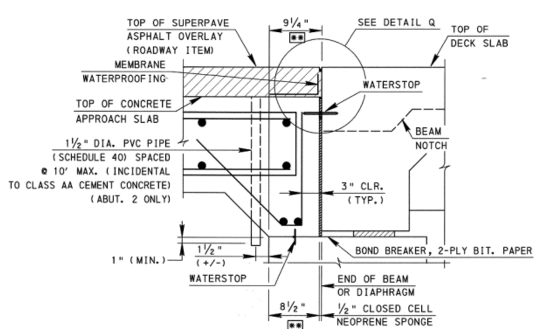


Figure C98: Details of Expansion joint

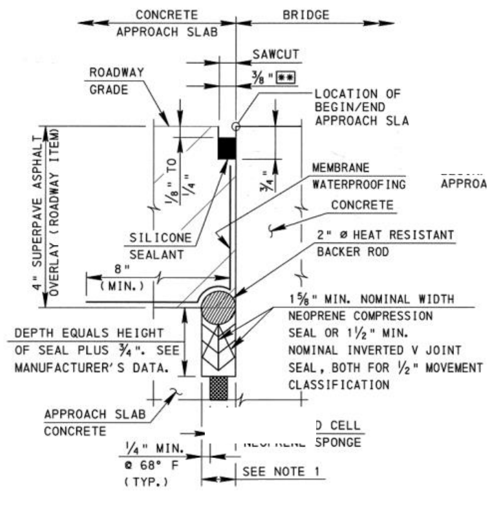


Figure C99: Detail Q in figure C98

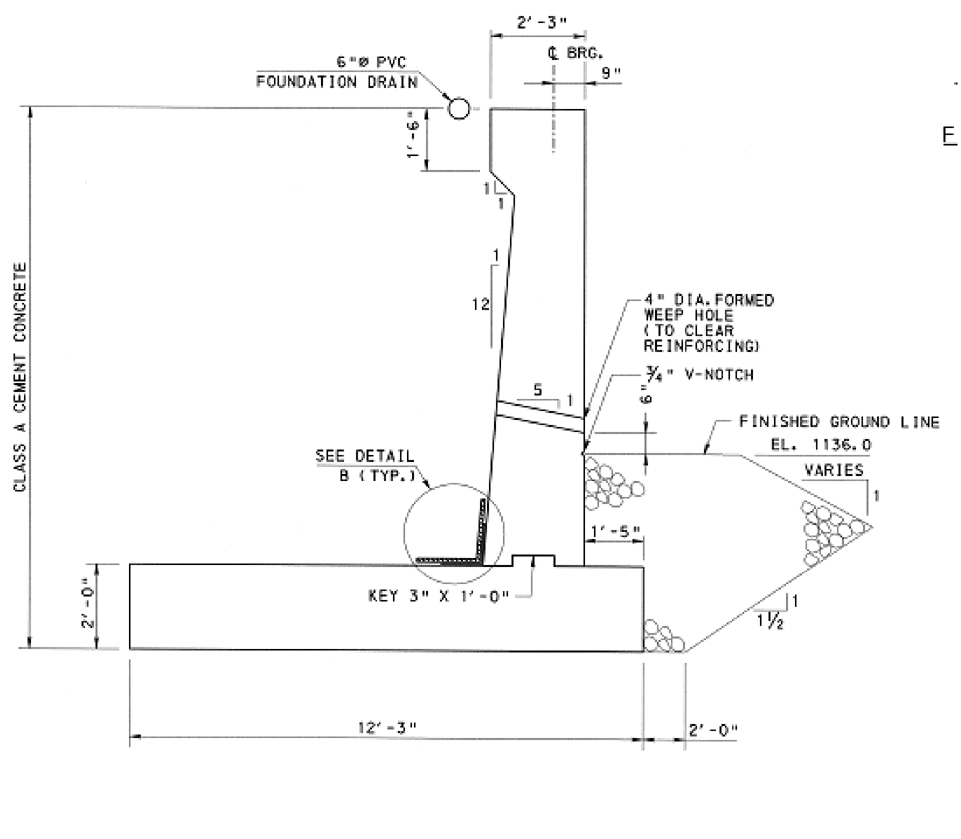


Figure C100: Section of retaining wall in abutment

Figure C101: Slight deterioration of HMA surface adjacent to joint

Figure C102: Severe water staining on abutment wall

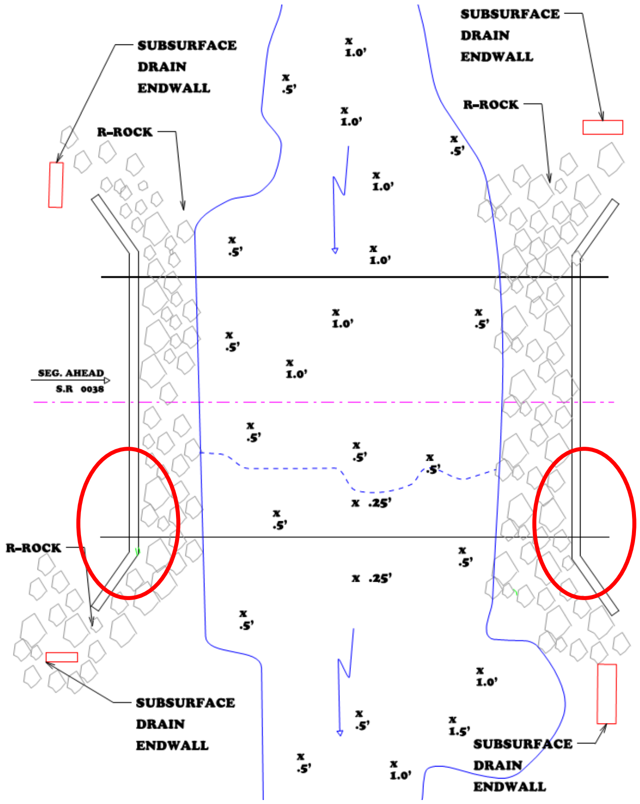


Figure C103: Locations of severe water staining (circled areas)

Figure C104: Weep hole on retaining wall

Figure C105: Minor debris accumulation along the edge of the deck

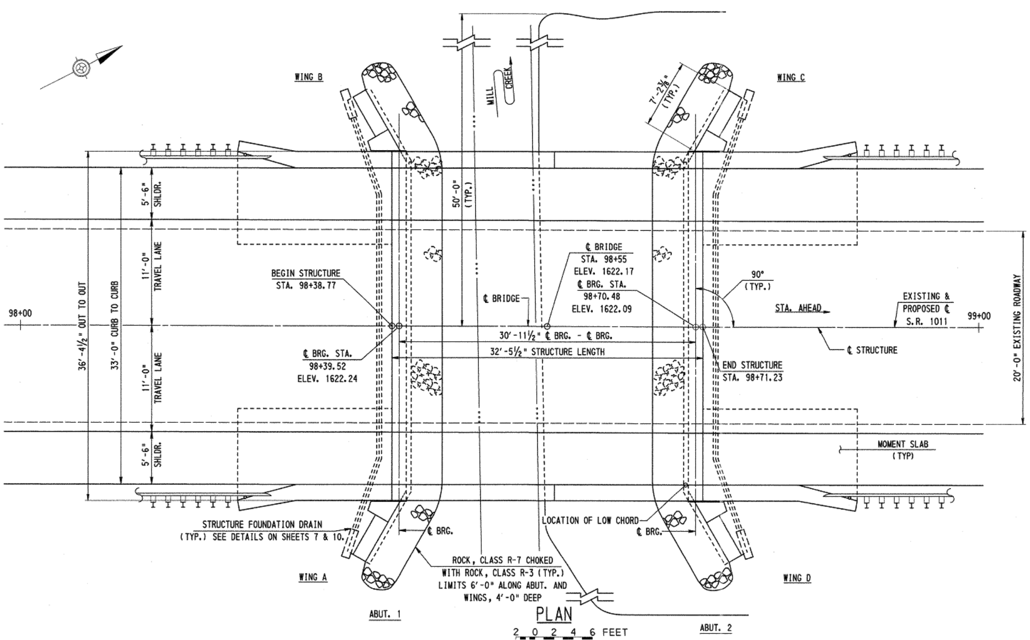


Figure C106: Plan of Beechton Bridge

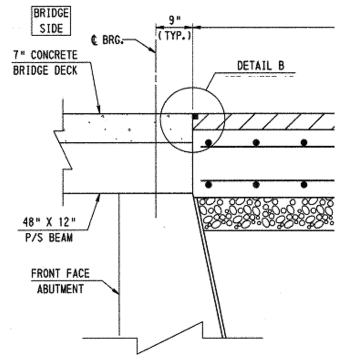


Figure C107: Expansion joint at bridge deck – moment slab interface

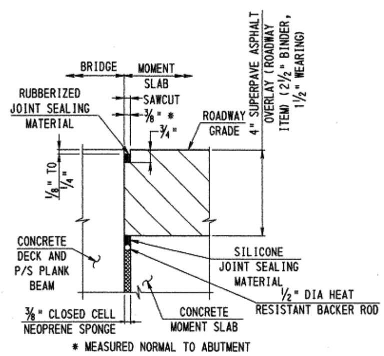


Figure C108: Detail B in figure C107

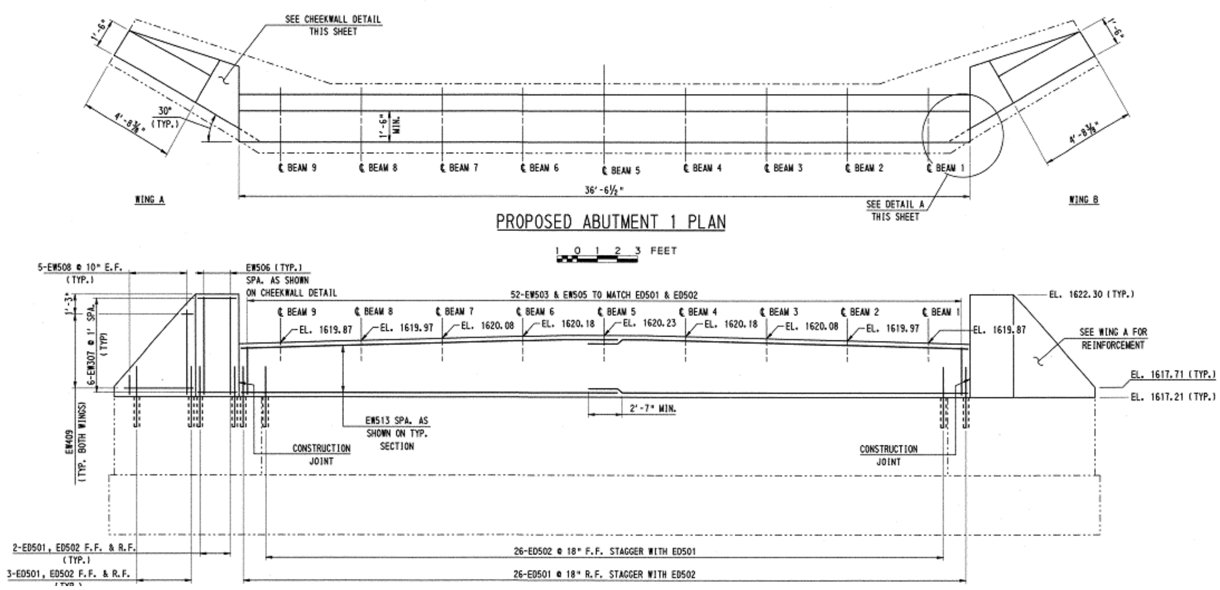


Figure C109: Plan of abutment

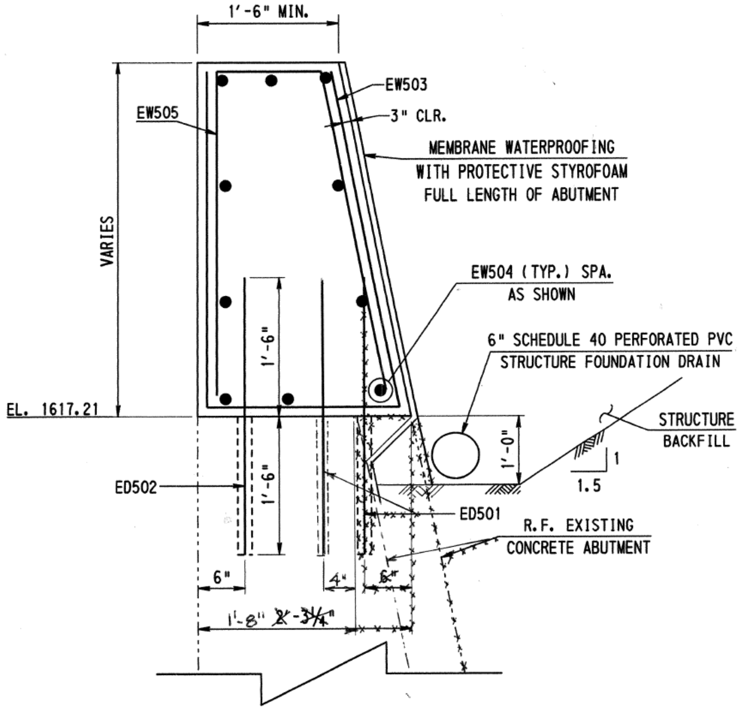


Figure C110: Section of Abutment

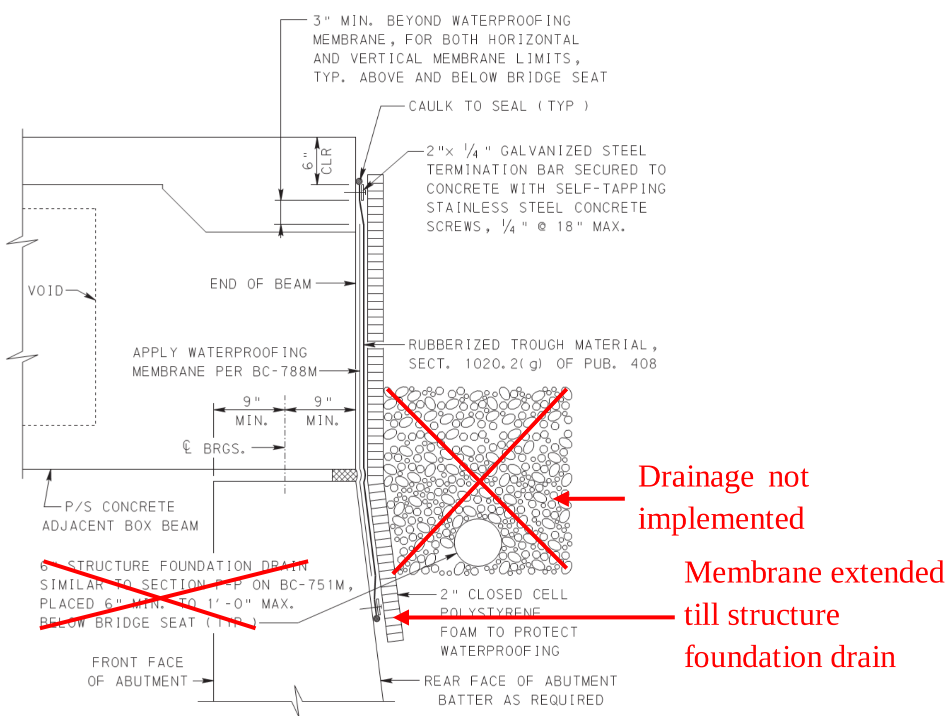


Figure C111: Waterproofing details at abutment-expansion joint interface

Figure C112: Staining of abutment wall observed by PennDOT inspectors

Figure C113: Severe leakage from interface of new and old abutment sections

Figure C114: Leakage at cracks originating from interface of new and old abutment sections

Figure C115: Waterproofing at approach slab – bridge deck interface

Figure C116: Waterstop extended to curb overlapping on additional piece of waterstop

Figure C117: Polystyrene foam fillers in between approach slab and bridge deck

Figure C118: Bridge on SR0028 over Cowanshannock Creek

Figure C119: Amherst Bridge

Figure C120: Bridgewater-Middleborough Bridge

Figure C121: Hanover Bridge

Figure C122: South Hadley Bridge

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