Evaluation of Box Culvert Differential Settlements Subject to Highway Embankment Load

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Fish Passage Concrete Culvert

(Example)

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Image from: https://abc-utc.fiu.edu/mc-events/precast-concrete-culvert-standards-for-wsdot-fish-passage-projects/?mc_id=727

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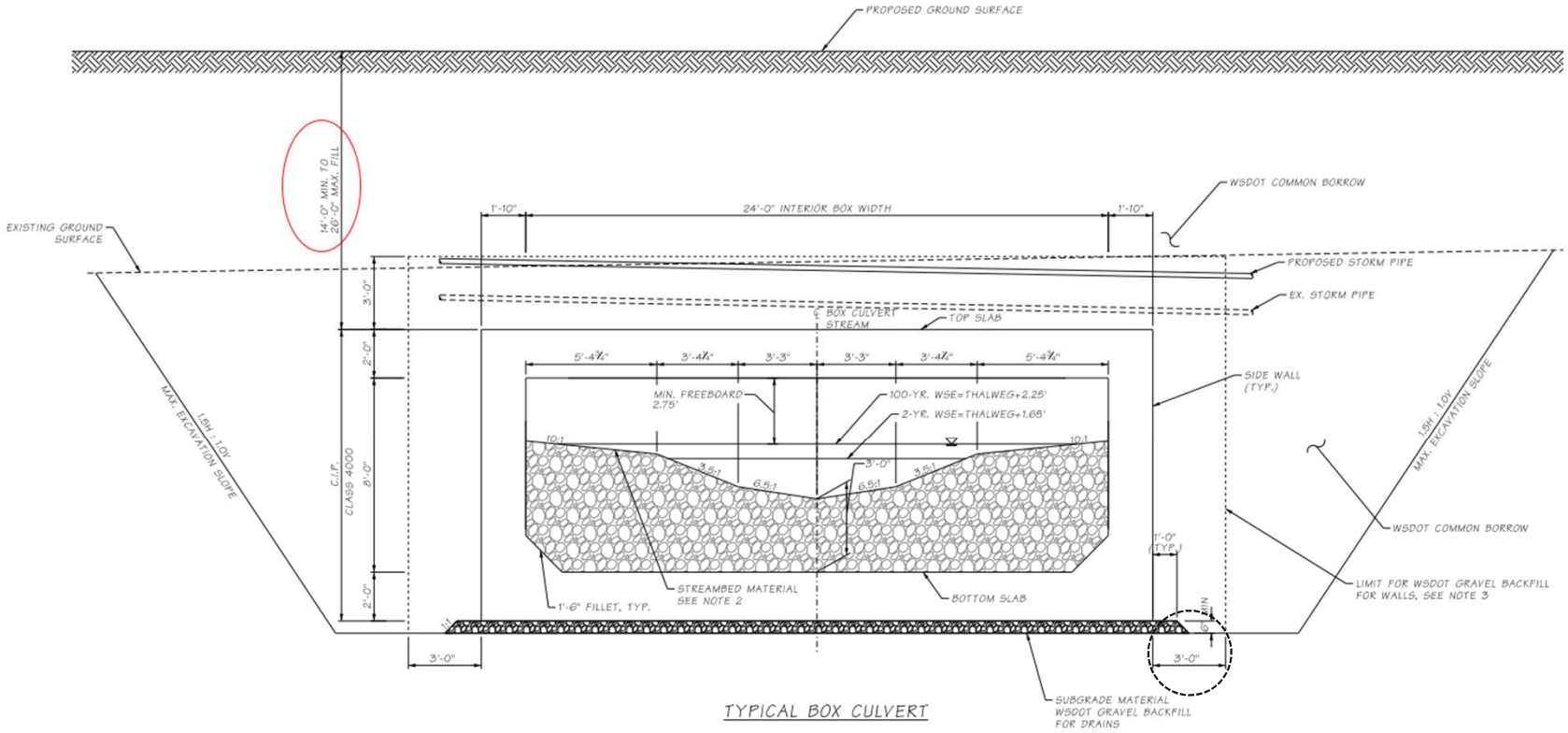

TYPICAL BOX CULVERT

3. WSDOT GRAVEL BACKFILL FOR WALLS ARE INSTALLED IMMEDIATELY 3 FEET BEHIND THE SIDE WALLS AND ABOVE THE CULVERT TOP SLAB.

Box Culvert Design General Considerations

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- Consider the box culvert as a beam in structural design.
- Design against **At-Rest** lateral earth pressures .
- Design groundwater at 100-yrs flood elevation .
- Place Drainage Coarse Aggregate Below Base Slab and a min, 3-ft Thick on Both Sides of the Culvert.
  - Reduce Differential Hydrostatic Pressure between Outside & Inside of the Culvert

Box Culvert Design Settlement Criteria

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- WSDOT 2015 GDM (Geotechnical Design Manual) requires

Total Settlement	Differential Settlement Over 100 Feet	Action
$\Delta H \leq 1$ in	$\Delta H_{100} \leq 0.75$ in	Design and Construct
1 in $< \Delta H \leq 2.5$ in	0.75 in $< \Delta H_{100} \leq 2$ in	Ensure structure can tolerate settlement
$\Delta H > 2.5$ in	$\Delta H_{100} > 2$ in	Obtain Approval[1] prior to proceeding with design and Construction

[1]Approval of WSDOT State Geotechnical Engineer and WSDOT Bridge Design Engineer required.

Settlement Criteria for Cut and Cover Tunnels, Concrete Culverts (including box culverts), and Concrete Pipe Arches
Table 8-5

where ΔH_{100} is differential settlement over 100 feet

Mitigating Total & Differential Settlements (Structurally)

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- Structure to be designed to tolerate min. 2-inch per 100ft differential displacement (WSDOT)
- Precast box culvert units with greater tolerance of differential settlement / angular distortion
- Enhance reinforcing steel (esp. base slab) to increase structural rigidity
- Optimize construction joint locations
- Install “Bond Beam/Link Slab” over joints of box culvert sections (FDOT Practice)

Reference: https://abc-utc.fiu.edu/mc-events/precast-concrete-culvert-standards-for-wsdot-fish-passage-projects/?mc_id=727

FDOT (2008)

"Bond Beam" over joints of box culvert sections

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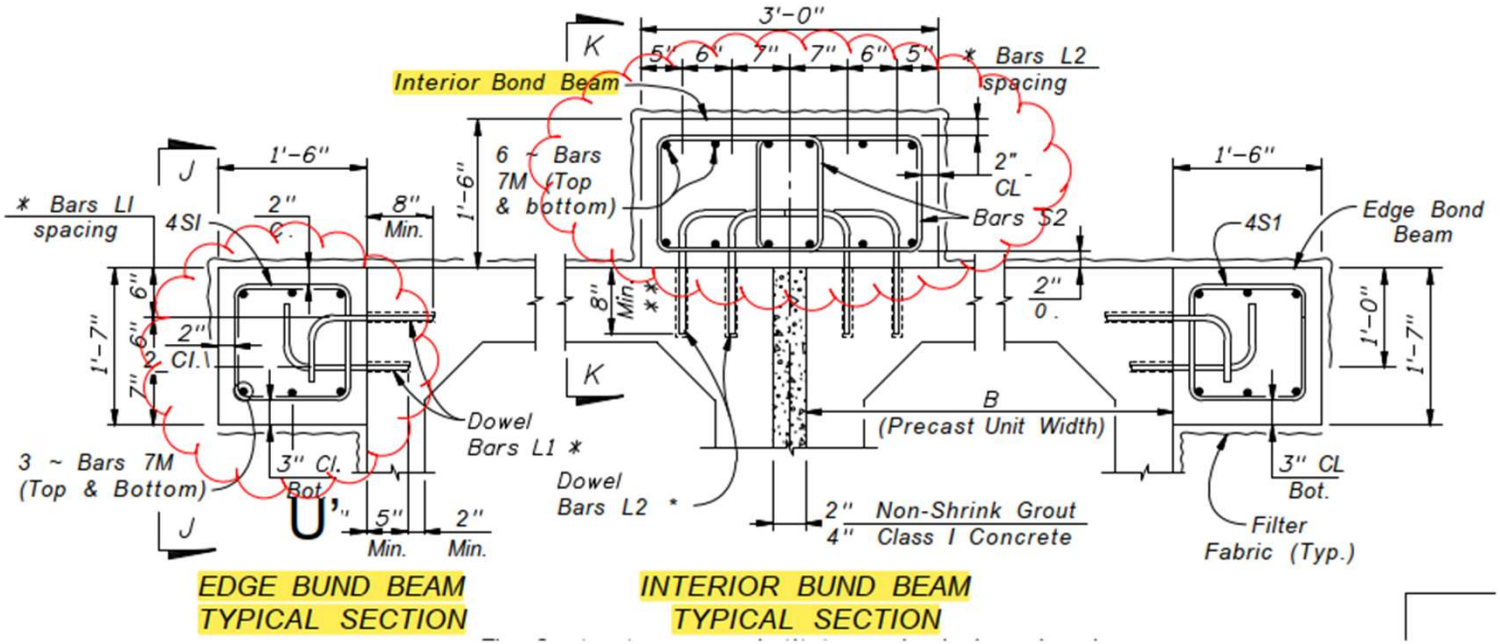

DIFFERENTIAL SETTLEMENT COUNTERMEASURES FOR PRECAST BOX CULVERTS

2008 FDOT Design Standards

SUPPLEMENTAL DETAILS FOR PRECAST CONCRETE BOX CULVERTS

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FDOT (2009 - 2024)

"Link Slab" over box culvert sections

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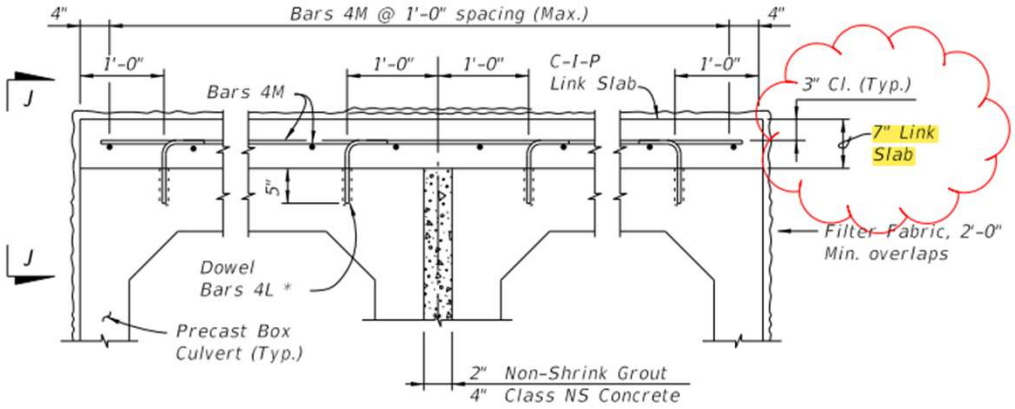
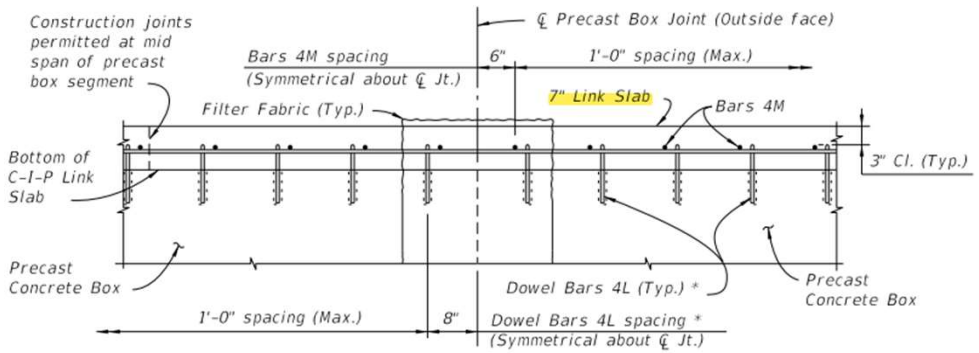


LINK SLAB TYPICAL SECTION
(Multiple Barrel Culvert shown, Single Barrel Culvert similar)



VIEW J-J

FDOT FY 2023-24 STANDARD PLANS	PRECAST CONCRETE BOX CULVERTS - SUPPLEMENTAL DETAILS	INDEX 400-291

FDOT (2024)

Q: When the Link Slab is required?

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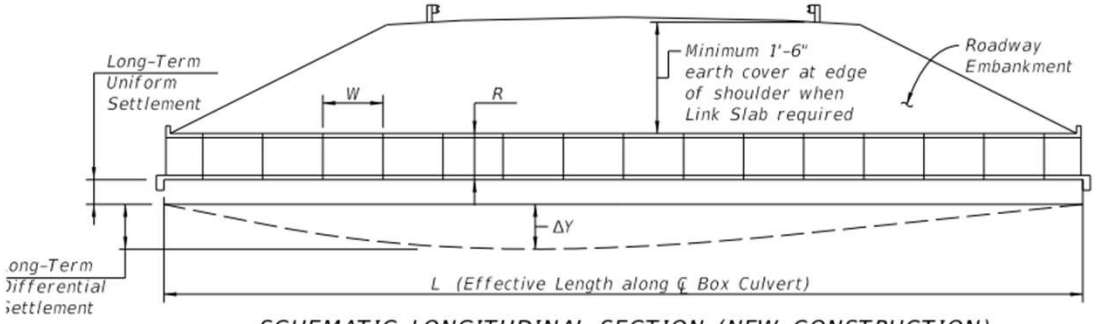
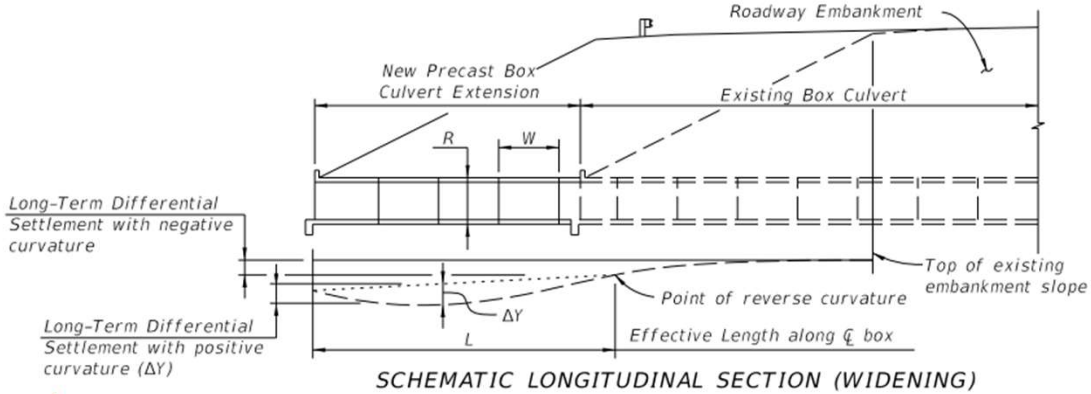


SCHEMATIC LONGITUDINAL SECTION (NEW CONSTRUCTION)



SCHEMATIC LONGITUDINAL SECTION (WIDENING)

1. Provide a Cast-In-Place Link Slab to ensure uniform joint opening of precast box culverts when the differential settlement shown in the plans exceeds the following limits, except that a Link Slab is not required for differential settlements less than ½".

$$\Delta Y \leq \frac{(L)^2}{760 \times R \times W}$$

Where:

- ΔY = Maximum Long-Term Differential Settlement (ft.)
- R = Exterior height of Box Culvert (ft.)
- W = Length of Box Culvert Segments (ft.)
- L = Effective length for single curvature deflection (ft.)

2. Extend Link Slab to back face of headwalls and to limits of existing box culverts for extensions.

DIFFERENTIAL SETTLEMENT COUNTERMEASURES FOR PRECAST BOX CULVERTS

FDOT	FY 2023-24 STANDARD PLANS	PRECAST CONCRETE BOX CULVERTS - SUPPLEMENTAL DETAILS	INDEX 400-291

Refrence: https://abc-utc.fiu.edu/mc-events/precast-concrete-culvert-standards-for-wsdot-fish-passage-projects/?mc_id=727

Mitigating Total & Differential Settlements (Structurally)

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Reference: ***https://abc-utc.fiu.edu/wp-content/uploads/2022/03/2022-03-17_WSDOT-Precast-Culvert-Standards-for-Fish-Passage-Projects.pdf***

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Mitigating Total & Differential Settlements (Geotechnically)

- Undercut of localized soft/loose compressible soils
- Limited undercut by placing heavy-duty geotextile over foundation subgrade
- Camber be placed over the bearing subgrade to compensate for settlement (NCDOT Practice)

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Mitigating Total & Differential Settlements (Geotechnically)

- Use of lightweight (0.7-2.5 pcf) Geofoam Expanded Polystyrene (EPS) block fill
  - Along section having greater embankment height or soft/loose compressible subgrade
  - Wrapped/Encapsulated with geomembrane
  - w/ Overburden resisting potential buoyancy

NCDOT Practice (2025)

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- **Camber** be placed over the bearing subgrade to compensate for settlement (NCDOT Practice)

"Where pipe culverts are placed on compressible material, camber should be placed in the grade of the pipeline to compensate for settlement. The amount of camber used depends on the load imposed on the foundation materials and the compressibility of the material. Since these factors vary, judgement is required in selecting the amount of camber to be used. In an effort to provide some guidance in the selection of values for camber, a chart (Camber Table) of these values is included in Appendix D of this Manual. Unless more precise information is available, the values taken from the chart should be used."

Ref: https://connect.ncdot.gov/resources/Materials/Pages/Drainage-User-Manual-Text.aspx?Method=DM-08-A#APPENDIX%20D%20CAMBER%20DETERMINATION

Camber for Box Culver

Camber Table

(Appendix D, NCDOT Drainage User Manual)

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- For continuous culverts beneath the entire width of the embankment, multiply the selected factor by the length of the culvert (L) to determine the midpoint camber.

CAMBER TABLE

Fill Height		Soil Type Factors		
(feet)	(meters)	medium	soft	very soft
0 to 10	0 to 3	0.0008	0.0013	0.0017
10 to 30	3 to 9	0.0017	0.0025	0.0033
30 to 50	9 to 15	0.0025	0.0038	0.0050

Ref: https://connect.ncdot.gov/resources/Materials/Pages/Drainage-User-Manual-Text.aspx?Method=DM-08-A#APPENDIX%20D%20CAMBER%20DETERMINATION

Camber for Box Culver
(Appendix D, NCDOT Drainage User Manual)

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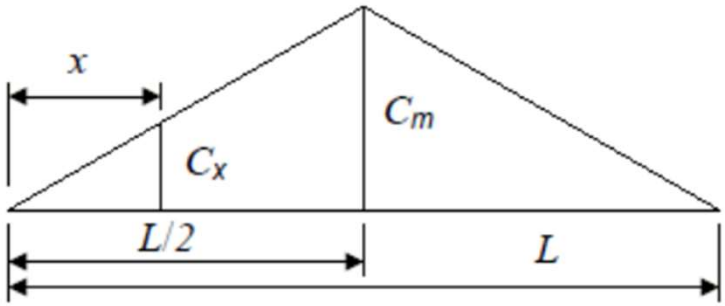
The mid point camber for pipe culverts shall be limited to one-half of the available fall in the pipe culvert or, (L/2) x (% grade), where L is the length of the culvert in feet (meters) and shall be limited to 2 ft (0.6 m). The proposed grade for the culvert at the midpoint (L/2 from the end of the culvert) should be adjusted upward by Cm where Cm is the smaller of the calculated camber and the limits stated above. The amount of camber Cx at any distance x along the length of the culvert that can be determined by:

$(C_m)\ (x \div (L/2))$, where x is any distance along the length of the culvert L.



Case Study – WSDOT I-405

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I-405 Bellevue to Renton Express Toll Lanes Design-Build Project

Client
Washington DOT
Flatiron/Lane JV

Location
King County, Washington

Project Duration
2019-present

Contract Value
$705 Million

WSP Role: Design Prime Team Member

- Geotechnical/Structural/Civil/ Roadway Design Leads
- Environmental (Fish passage and stream restoration)

Case Study

Fish Passage Box Culvert, WSDOT I-405

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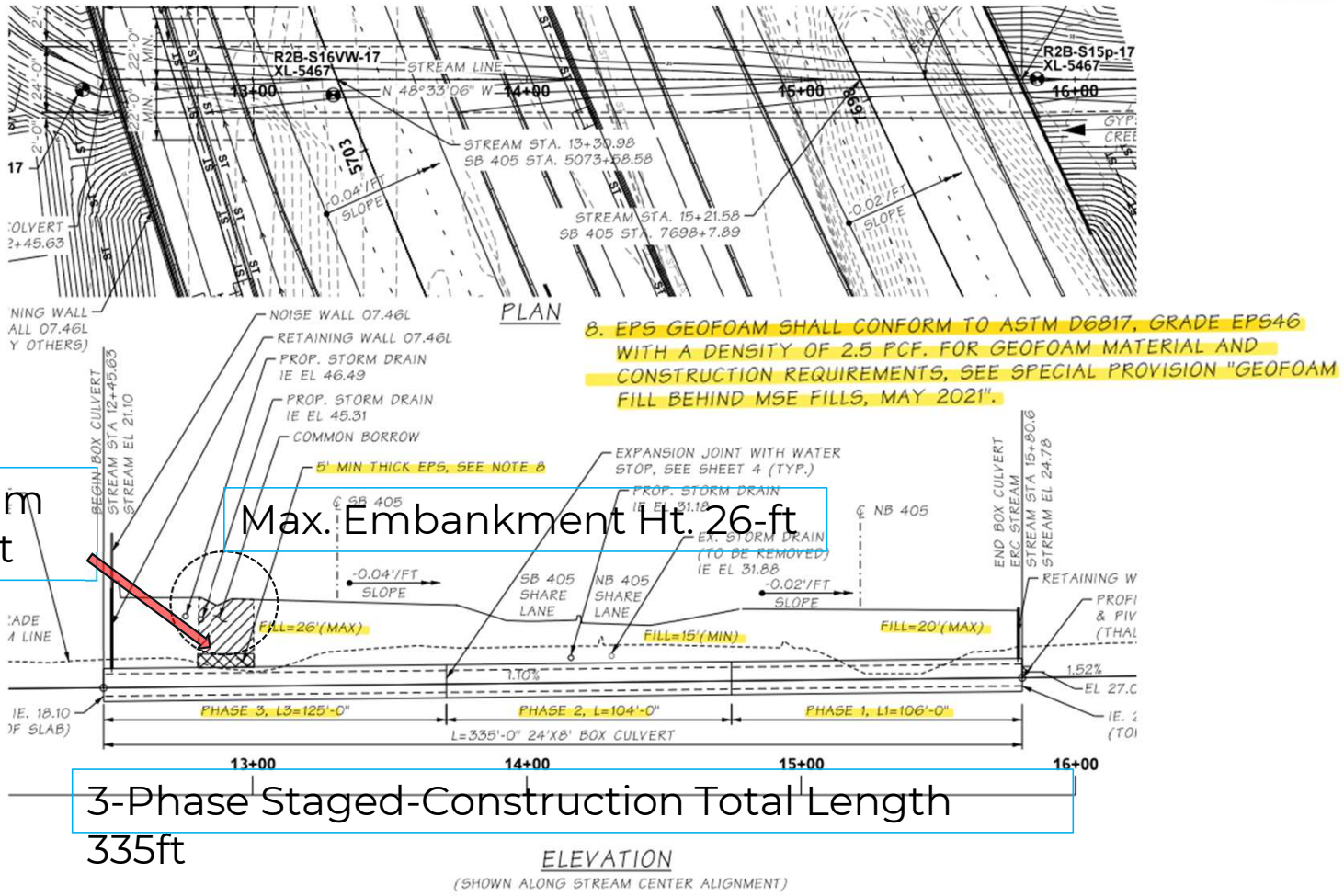
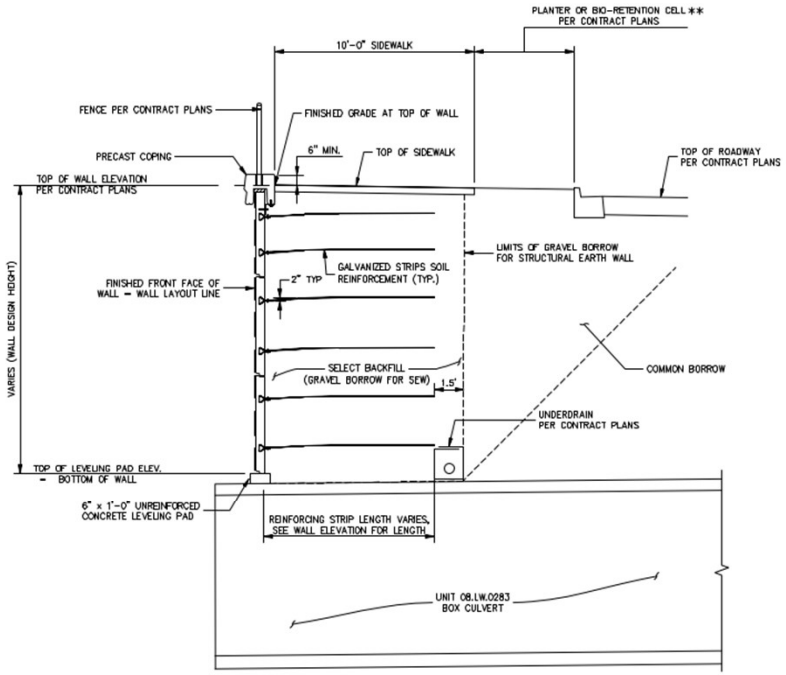


EPS Geofoam Lightweight Fill

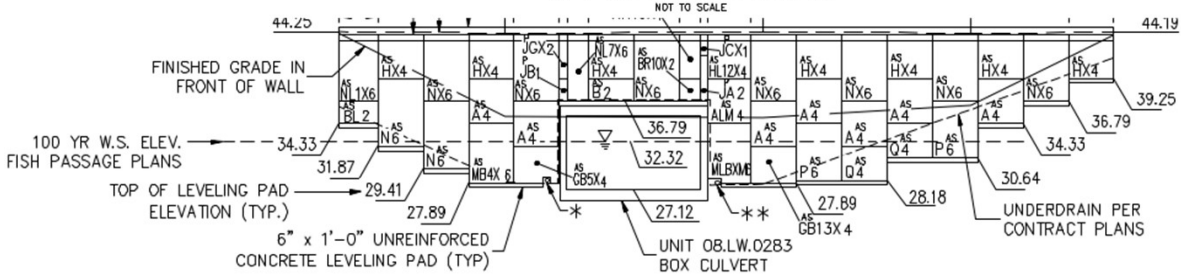
Max. Embankment Ht. 26-ft

3-Phase Staged-Construction Total Length 335ft



TYPICAL SECTION – STRUCTURAL EARTH WALL
AT I-405 FISH PASS CULVERT

NOT TO SCALE



Box Culvert Settlement Analysis

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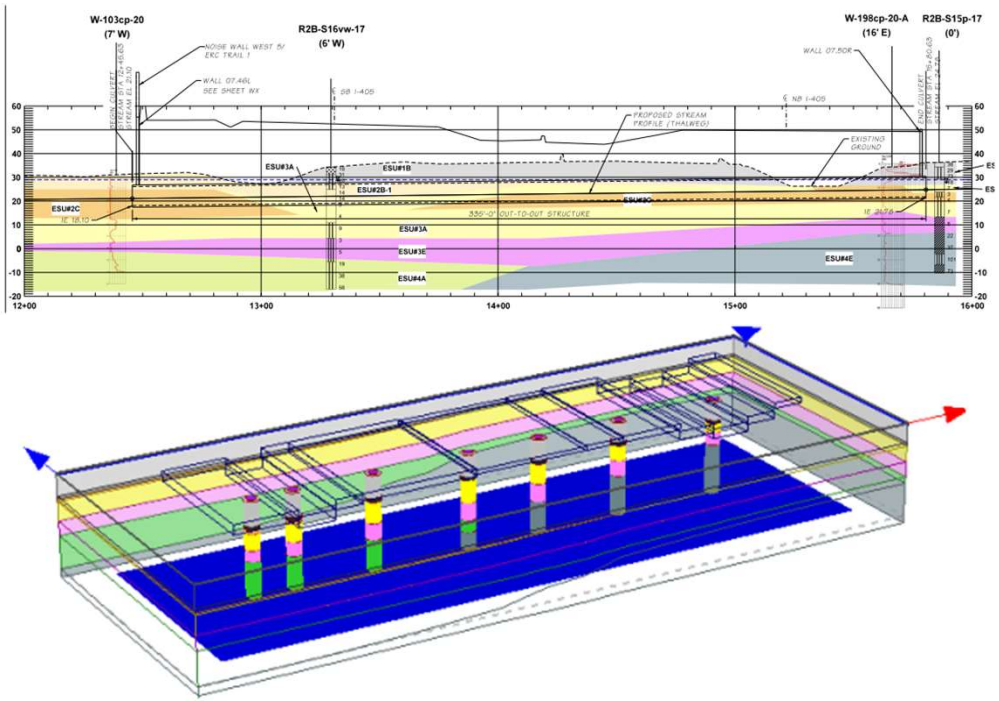
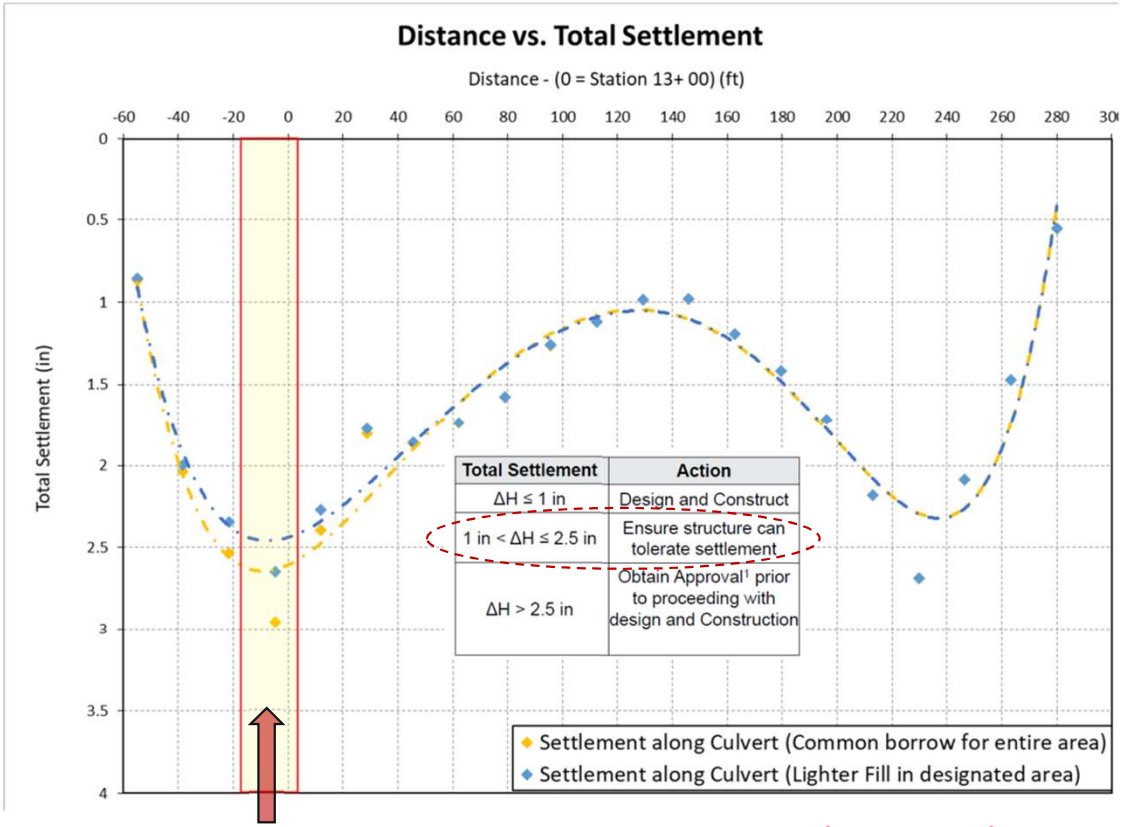


- Performed settlement analysis using ***Settle3*** *(developed by RocScience)* computer software.
- Set up 3-D soil profile & design soil parameters,
- Consider staged-construction sequence (excavation unloading & loading), w/ planned limited undercut.

Results of Settlement Analysis

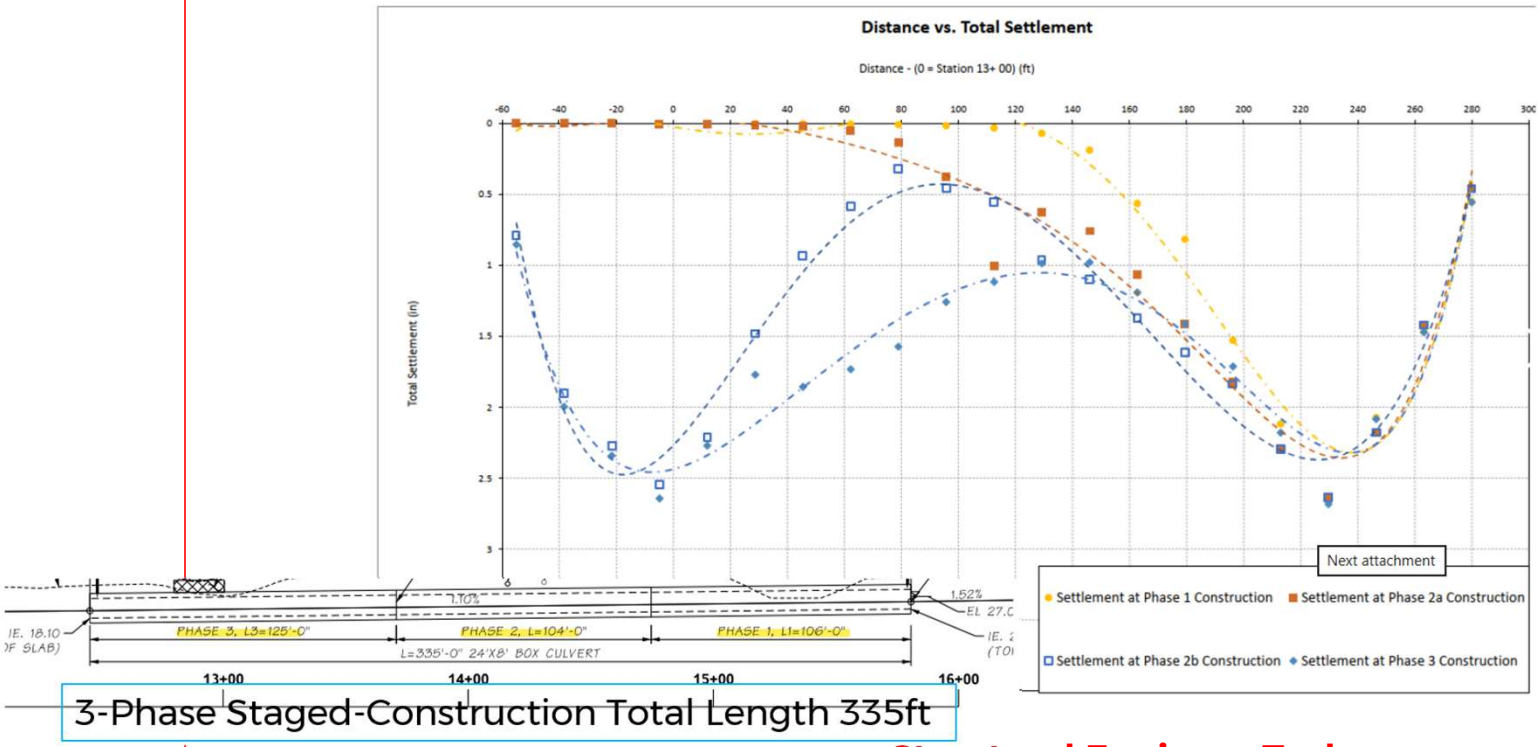
Final Total Settlement Profile



- To meet the Action requirement, **Lightweight Geofoam Embankment Fill** is used to reduce the total settlement.

Results of Settlement Analysis

3-Phase Staged-Construction Settlement Profiles



3-Phase Staged-Construction Total Length 335ft

Structural Engineer Tasks

- Determine Design Subgrade Modulus ($K=P/\Delta$) based on the **incremental** settlement (Δ) and Service Limit Design Loading (P),
- Design reinforcing steel of cast-in-place (CIP) box culvert sections.

Temporary Structural Earth Wall (SEW) during Staged-Construction

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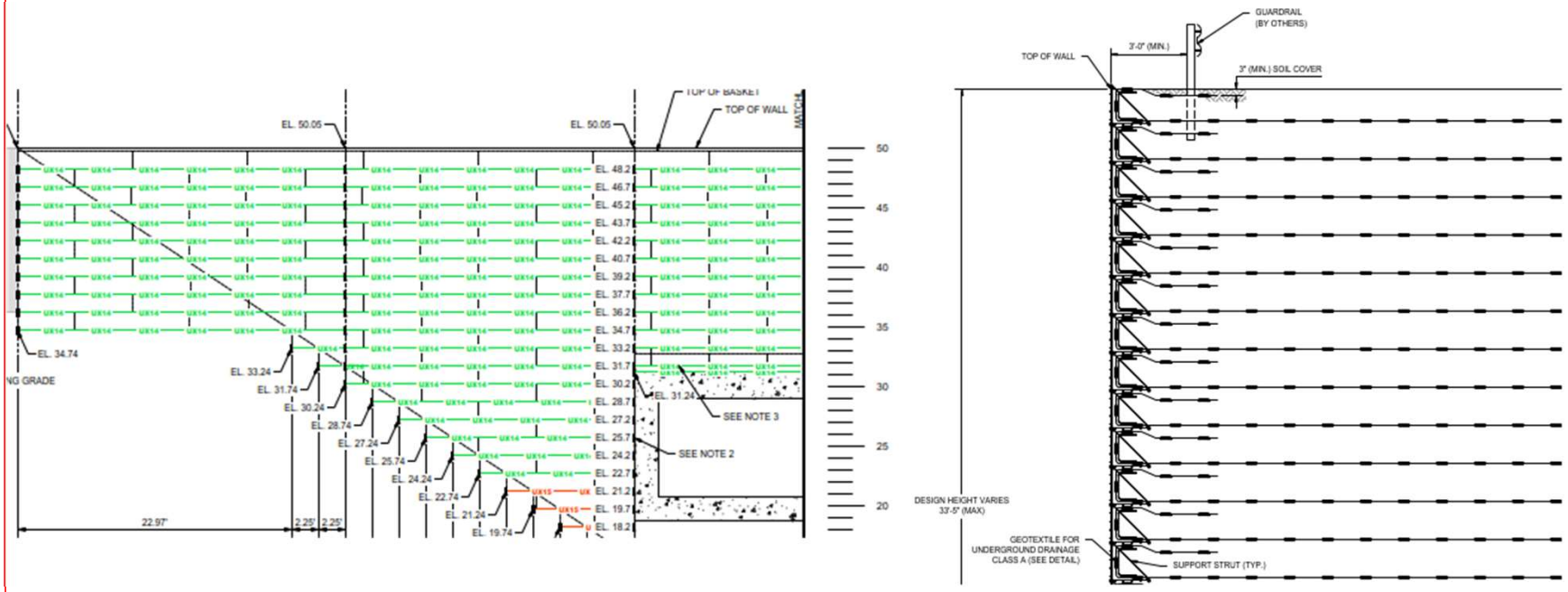
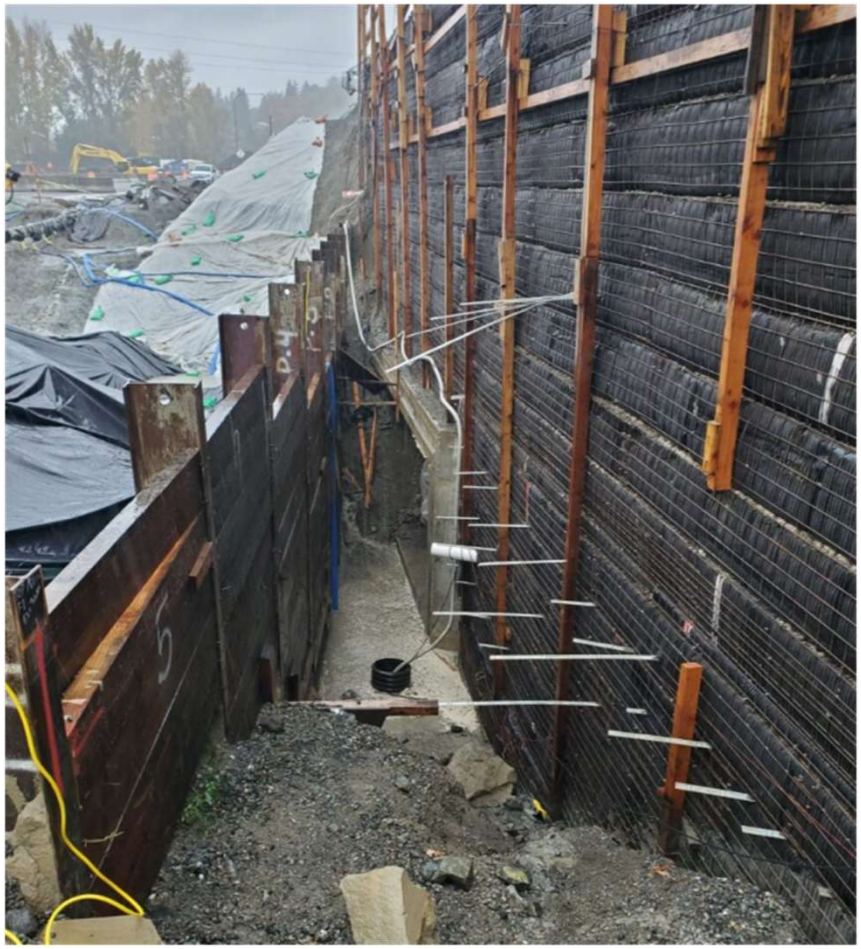
- Staged Construction (3-Phases) w/ Monitoring



Temporary Structural Earth Wall (SEW) during Staged-Construction



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Temporary Culvert Bulkhead during Staged-Construction

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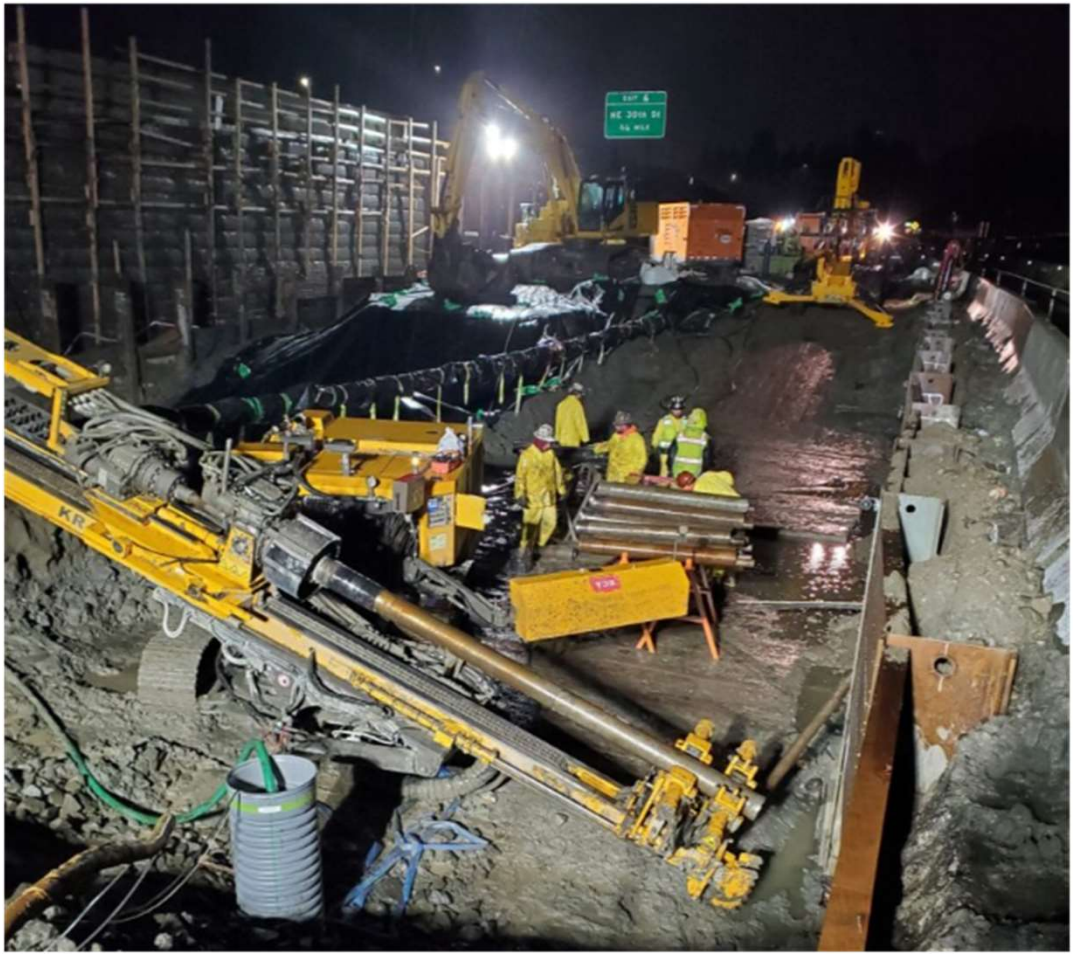

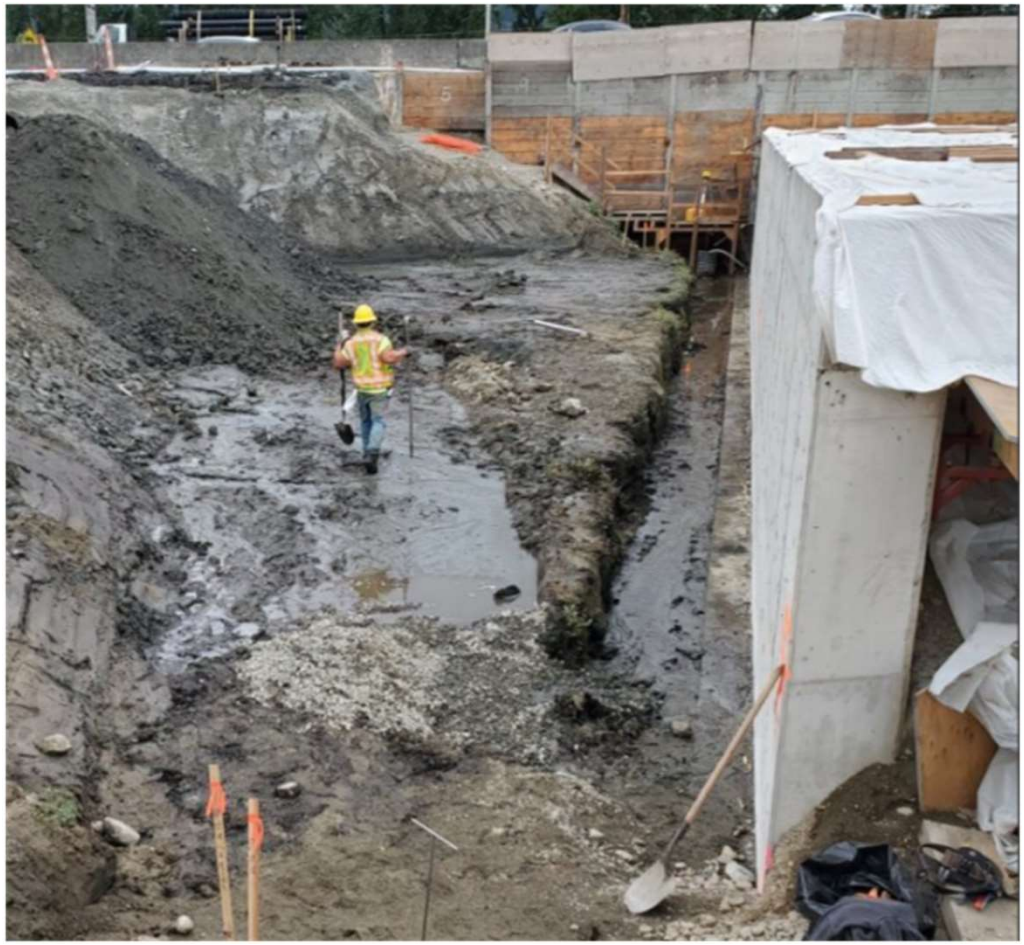

Summary and Future Questions

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- Given the nature of the delivery method (design-build), expeditious communication among geotechnical, structural, contractor, and the DOT was necessary. Within a narrow timeframe, the group addressed differential settlement/angular distortion issues and facilitated construction within critical weekend closure periods.

- Soil-Structure Interactions

  When subject to embankment loading, pressures acting on the box culvert roof slab could be different from those experienced at the base of the culvert.

  (Reference: Section 12.2.2 in *Soil-Structure Interaction. The real behaviour of structures.* The Institution of Structural Engineers, March 1989)

Thank you

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