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BUILDING A SUSTAINABLE TRANSPORTATION LEGACY

PATTULLO BRIDGE REPLACEMENT - SURREY MULTI-USE PATH STRUCTURE: DESIGN & CONSTRUCTION CHALLENGES

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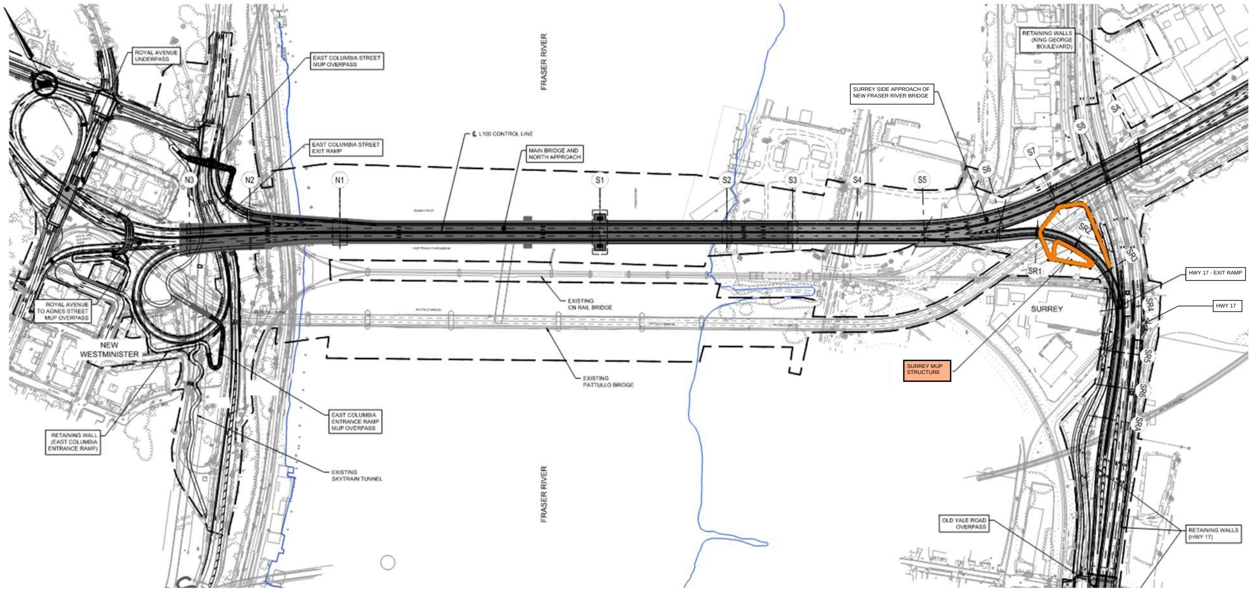
ABSTRACT: The Existing Pattullo Bridge over Fraser River in greater Vancouver area was built in 1937 to carry vehicular and pedestrian traffic between the City of Surrey and New Westminster. Over the period, it has become difficult to drive on its existing narrow lanes without median barrier. Moreover, the existing Pattullo Bridge does not meet the current seismic standards. The Pattullo Bridge Replacement Project is a solution to all the above-mentioned problems. The multi-use path (MUP) connection to the new bridge in Surrey is a vital component of the Pattullo Bridge Replacement Project. Its primary function is to ensure the uninterrupted movement of pedestrians and cyclists across the new bridge and between the new bridge and ground level beneath the new bridge in Surrey. It is an 11 span 4.0m wide Multi-User Path (MUP) Structure in an area full of geotechnical and environmental constraints. Due to significant drop in elevation required in limited available space, the MUP connection structure in Surrey is a 2-level composite steel girder bridge which spirals over multiple concrete piers supported by steel pipe piles. This paper discusses the challenges faced during design and construction of this unique structure due to its extremely irregular geometry, proximity to existing Pattullo Bridge and soils with potential to liquefaction and settlement. Moreover, Surrey MUP Structure is located in an area full of cultural and environmental constraints. Finite element analysis of Surrey MUP Structure was performed for its design and to check its seismic interaction with two other adjacent bridges sharing piers with it. An Expanded Polystyrene (EPS) foam embankment was proposed past abutment due to potentially settleable subgrade soils. All of this led to achieving a constructable solution for this bridge, hence meeting project functional requirements.

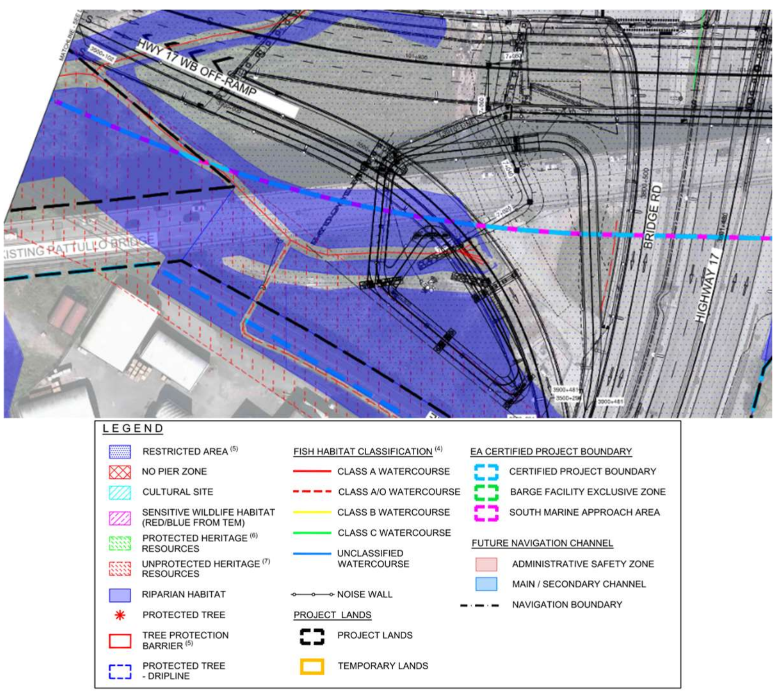
1 INTRODUCTION

In Pattullo Bridge Replacement Project, the multi-use path along the New Westminster to Surrey traffic on the New Fraser River Bridge gets interrupted at the Hwy 17 exit ramp as it continues along the Hwy 17 exit ramp. The Surrey MUP Structure has two primary functions: Firstly, to ensure the continuity of the MUP by connecting it back to the Surrey side approach of the New Fraser River Bridge and secondly, to bring cyclists and pedestrians down from the New Fraser River Bridge to the ground level along Hwy 17. It consists of 11 simply supported spans over two levels carrying a 4.0m (clear) wide MUP. The length of spans ranges from 16m to 40m depending on the location. The sum of lengths of all the spans in Surrey MUP Structure is 329m. After the abutment, the Surrey MUP continues for another 73m as an embankment. All the new MUP structures in the Pattullo Bridge Replacement Project are typically 4.0m wide which will ensure smooth and conflict free flow of cyclist and pedestrian traffic over these MUP structures. To meet the elevation difference, of approx. 15m, between the top and bottom of the Surrey MUP Structure, most spans have a longitudinal grade of 5%. Surrey MUP is being constructed in an area full of environmental and heritage constraints due to which the structure is extremely irregular. The subsurface soil is mostly liquifiable. On top of all these challenges, it is in Greater Vancouver Area where mega earthquake is due any time now. This paper contains an introduction to Surrey MUP and some of the challenges faced and expected during its design and construction.

2 LOCATION

The Surrey MUP Structure is located on the south side of new cable stayed bridge. It is classified as Major Route structure. At the top, Surrey MUP Structure connects to two other structures: firstly, to the Surrey side approach of the New Fraser River Bridge and secondly to the Hwy 17 Exit Ramp bridge. At the lower end past the Abutment, the Surrey MUP continues as EPS embankment and finally connects to the Bridge Road along Highway 17.



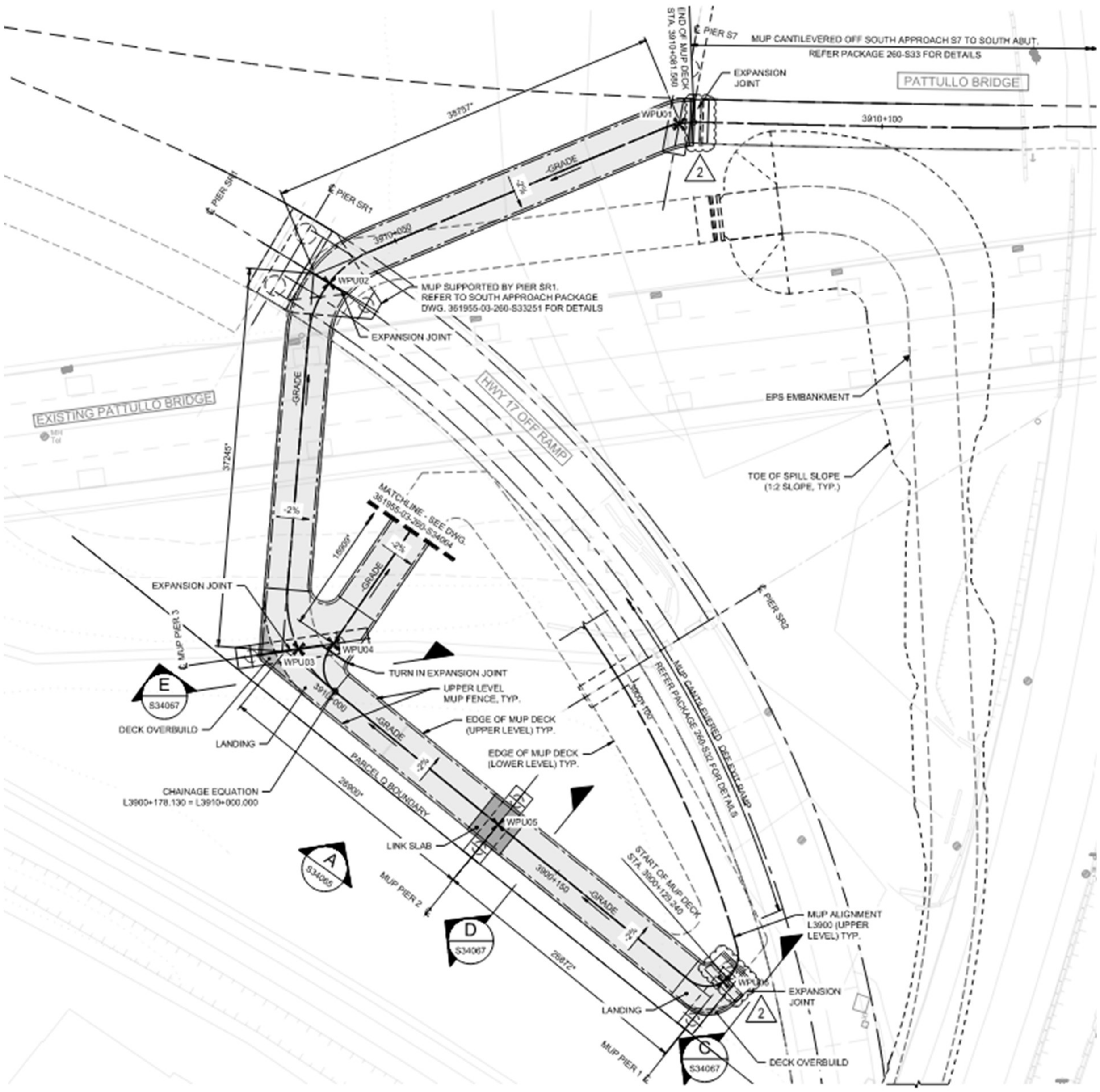


3 STRUCTURAL CONFIGURATION

3.1 Superstructure

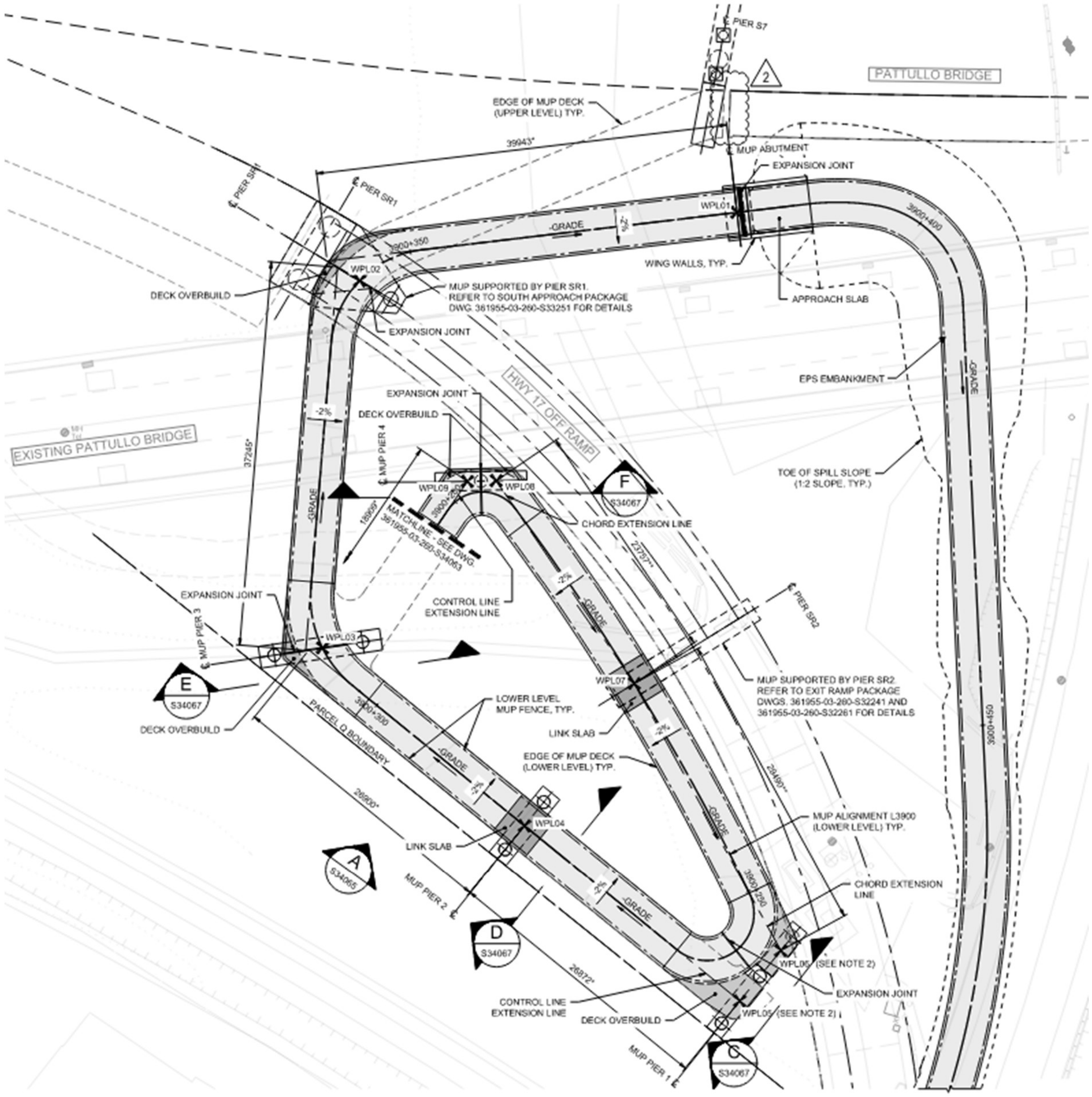
Surrey MUP superstructure consists of composite steel girders with concrete deck. The concrete deck, on both upper and lower levels, is 4m wide between the railings and supported by two steel girders typically 2.5m apart at center. The deck thickness is typically 235mm where precast panels are located (100mm precast concrete panels with 135mm CIP concrete on top) and 235mm-285mm (depending on location) where the deck is CIP Concrete only. While the concrete deck is connected to the steel girders using shear studs, it is disconnected at the link slab locations where no shear studs has been used. The steel I girders have two different heights, 1160mm for shorter spans and 1470mm for longer spans out to out. There are steel diaphragms at each end of the spans and steel cross fames at approx. 5.8m spacing along the span.



PLAN - UPPER LEVEL

SCALE 1:250



PLAN - LOWER LEVEL

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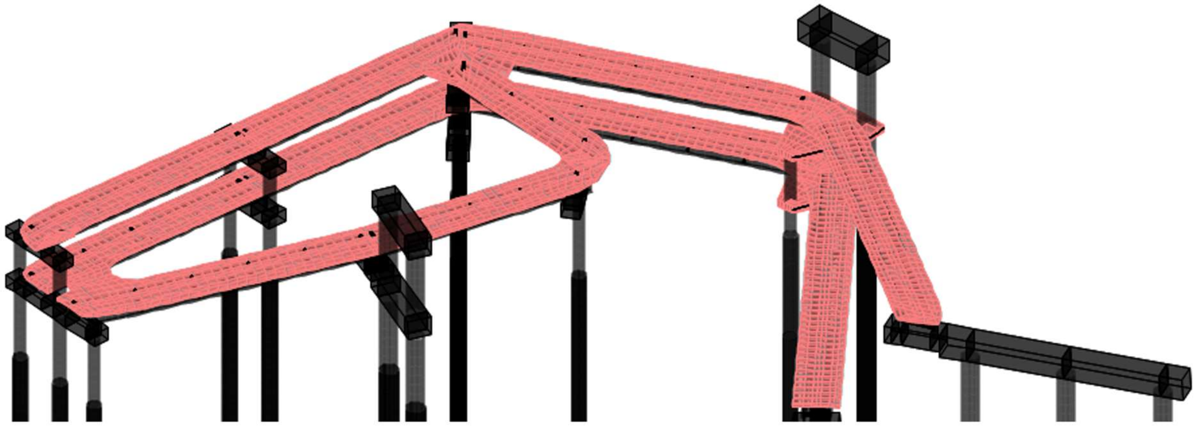
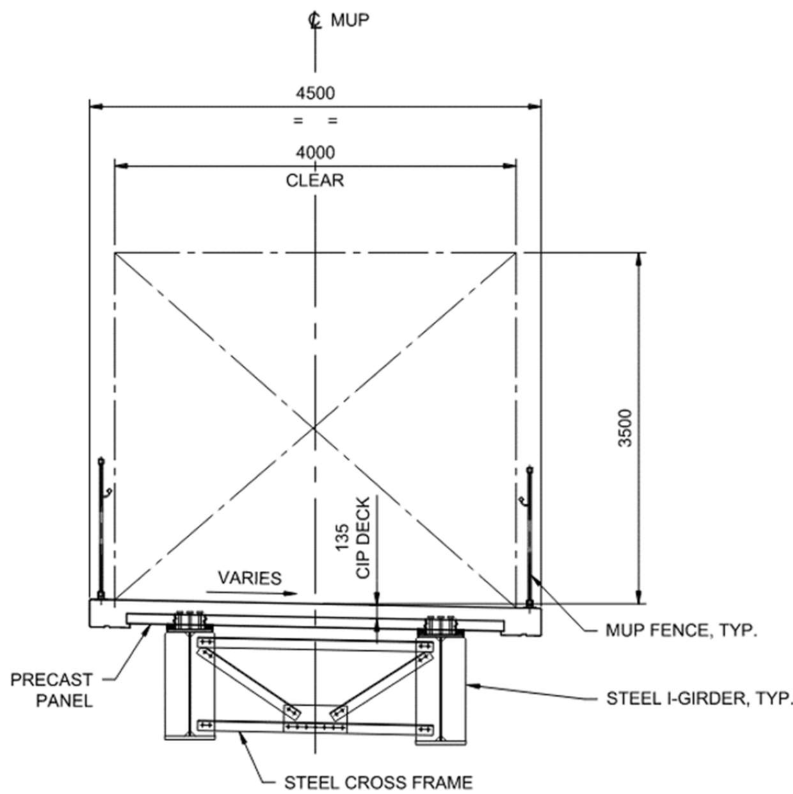


Superstructure Finite Element Model

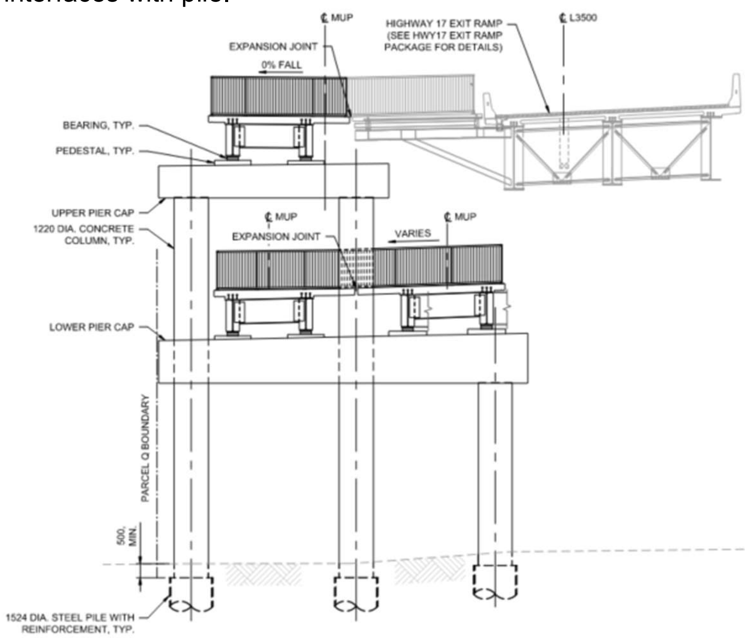


Typical MUP Superstructure Section

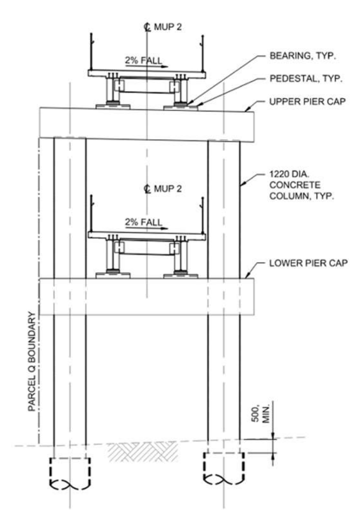
3.2 Substructure

The Surrey MUP Substructure comprises of fours piers and one abutment. These are identified as MUP Pier-1 (MUP1), MUP Pier-2 (MUP2), MUP Pier-3 (MUP3), MUP Pier-4 (MUP4) and Abutment (Abut). In addition, the Surrey MUP structure uses piers of other structures which are Hwy 17 Exit Ramp Pier-1 (SR1), Hwy 17 Exit Ramp Pier-2 (SR2) and New Fraser River Bridge South Approach Pier-7 (S7).

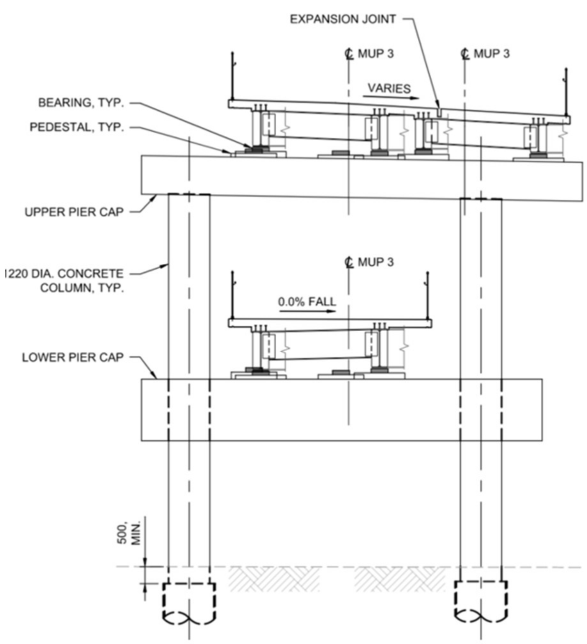
All the piers are extended pile bent type to avoid the need for pile cap thus minimizing ground disturbance. MUP1 has 3 columns, MUP2 and MUP3 each has 2 columns, MUP 4 and Abut both are hammer headed piers. All columns have 1220mm diameter. The Abut does not have a column and Abut pier cap directly interfaces with pile.



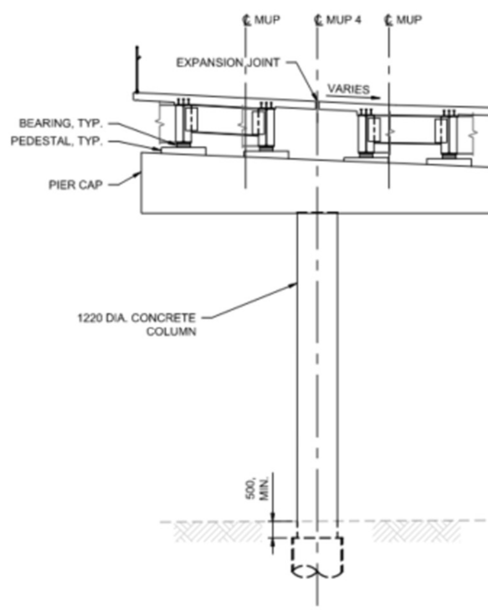
MUP1 Structural Type



MUP2 Structural Type



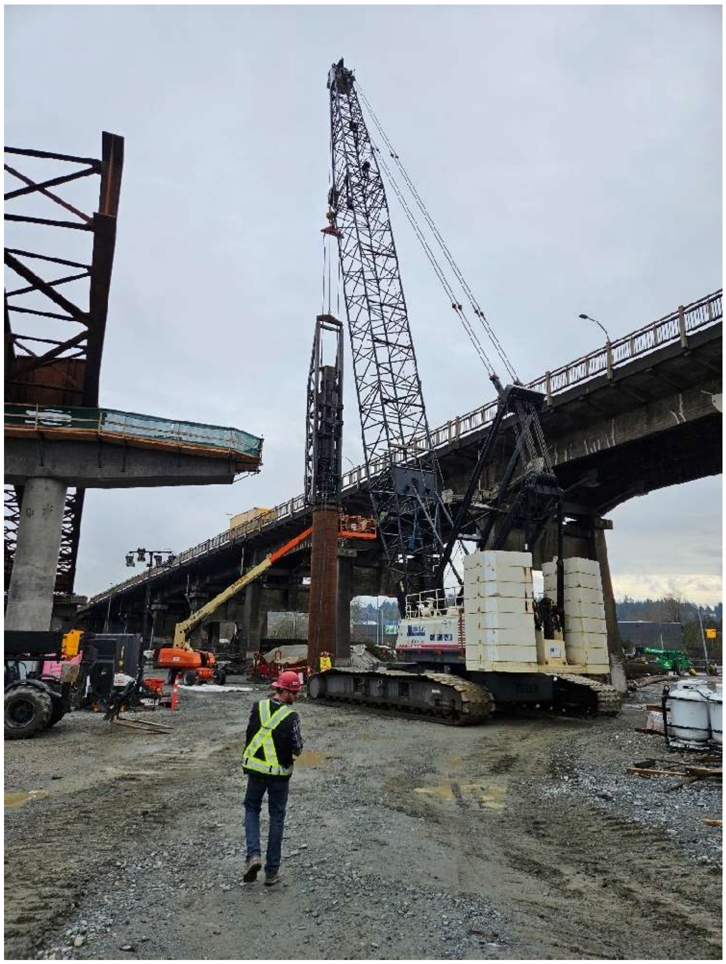
MUP3 Structural Type



MUP4 Structural Type

3.3 Foundation

All MUP piers are supported by 1524mm outer diameter (OD) piles consisting of reinforced concrete filled steel tubes. All piles have concrete plug which extends down to a depth where pipe section alone can resist loads, or typically just past the depth of liquefaction. The plug transfers the column loads into the pile and works compositely with steel pipes to withstand kinematic loads. Shear rings are provided on inside of all pipe piles to transfer axial loads from plug to pipe pile. Moment transfer is via wrenching action caused by plug bearing against pipe in the top transition zone.



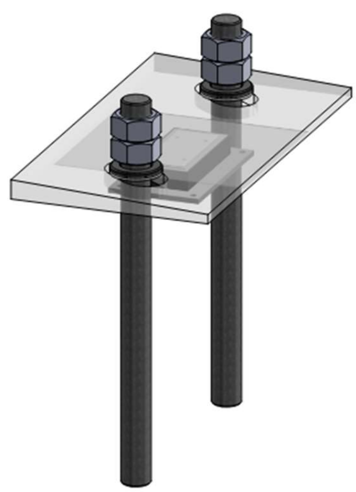
PDA testing at every pile location has been proposed in accordance with Project Agreement. The quality of plug concrete has been proposed to be verified during construction via Thermal Integrity Profiling (TIP) testing.

The details of information related to pile materials, thickness, pile plug, and estimated pile depth are summarized in the following table extracted from the design drawings:

BENT	PILE ID	NORTHNG (m)	EASTING (m)	PIPE PILE CUT-OFF EL. (m)	ESTIMATED MIN. PILE TIP EL. (m)	CONCRETE PLUG EL. (m)	STEEL PIPE PILE SIZE (API GRADE X52)					
							1524mm OD x 35mm THK.		1524mm OD x 30mm THK.		1524mm OD x 25mm THK.	
							START EL. (m)	END EL. (m)	START EL. (m)	END EL. (m)	START EL. (m)	ESTIMATED MIN. PILE TIP EL. (m)
PIER MUP1	MUP1-1	5450268.655	508378.094	1.890	-66.000	-28.000	N/A	N/A	1.890	-30.000	-30.000	-66.000
	MUP1-2	5450264.821	508374.968	1.532	-66.000	-28.000	N/A	N/A	1.532	-30.000	-30.000	-66.000
	MUP1-3	5450260.270	508371.259	1.510	-66.000	-28.000	N/A	N/A	1.510	-30.000	-30.000	-66.000
PIER MUP2	MUP2-1	5450281.689	508354.051	2.129	-66.000	-28.000	N/A	N/A	2.129	-30.000	-30.000	-66.000
	MUP2-2	5450277.112	508350.320	1.941	-66.000	-28.000	N/A	N/A	1.941	-30.000	-30.000	-66.000
PIER MUP3	MUP3-1	5450297.170	508336.514	1.480	-75.000	-28.000	1.480	-21.000	-21.000	-39.000	-39.000	-75.000
	MUP3-2	5450295.894	508327.974	1.459	-75.000	-28.000	1.459	-21.000	-21.000	-39.000	-39.000	-75.000
PIER MUP4	MUP4-1	5450312.768	508347.969	1.367	-55.000	-28.000	N/A	N/A	1.267	-37.000	-37.000	-55.000
ABUTMENT	AB1	5450338.779	508372.745	1.683	-51.000	-28.000	N/A	N/A	1.683	-33.000	-33.000	-51.000

4 ARTICULATION ARRANGEMENTS

The superstructure is articulated on elastomeric bearings with restrainer pins at all piers. These bearings are mostly either longitudinally free and transversely fixed OR longitudinally fixed and transversely fixed with respect to girder. During seismic event, all the restrainer pins are expected to engage which means bearings will act as fixed both longitudinally and transversely.



Surrey MUP alignment is extremely winding, so deck is discontinued at each pier using expansion joints except at two piers MUP2 and SR2 for which the alignment of connection with the adjacent piers is relatively straight. At these piers, the deck is continuous using link slabs. The deck is de-bonded at link slabs, so no shear studs has been used at these locations.

5 ANALYSIS & DESIGN

5.1 Design loads

Following design loads were considered in the design of Surrey MUP Structure:

1. Dead loads
2. Live loads (Pedestrian Load = 4kPa; Maintenance Vehicle = 80kN)
3. Wind Load (1:50 years reference wind pressure of 0.47kPa for project location)
4. Earth pressures for abutment wing walls
5. Thermal loading (differential temp of 30^{o} C)
6. Seismic load (Inertial and Kinematic loading)

5.2 Seismic Design Criteria

Seismic design criteria for Surrey MUP structure can be summarized by the following table:

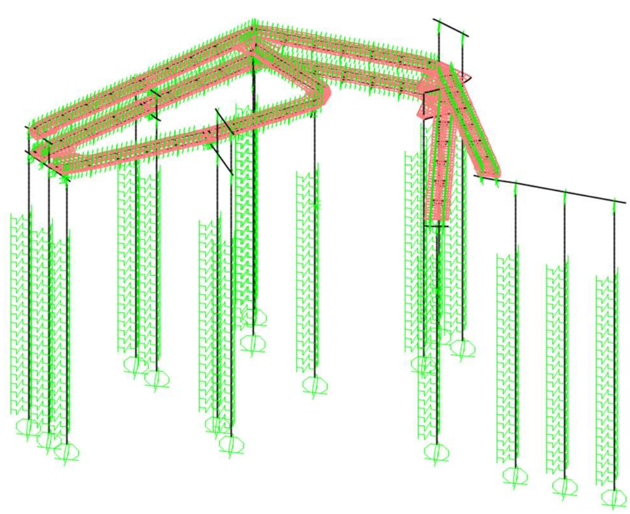
Regular or Irregular	*Irregular*
Bridge Seismic Design Importance Category	*Major Route*
Earthquake Analysis	*Elastic Dynamic Analysis and Inelastic Static Pushover Analysis*
Ductile Substructure Elements (Typical)	*Ductile Reinforced Concrete Columns*
Performance Objectives	*Per CSA-S6-14 BC Supplement*

5.3 Software Used

SAP2000, S-Concrete, Excel

5.4 Finite Element Analysis

Analysis of the bridge superstructure, substructure and pile foundations was performed using 3D finite element (FEM) model software SAP2000. The Finite element method was utilized for the analysis of girder for dead, live, thermal, wind and seismic load effects, both before and after deck composite action as applicable. The soil spring stiffnesses were derived from p-y curves provided by the Geotechnical Engineer. Design of precast concrete deck panels and cast-in-place concrete deck topping were designed according to Clause 5.7.1 of CSA-S6-14.

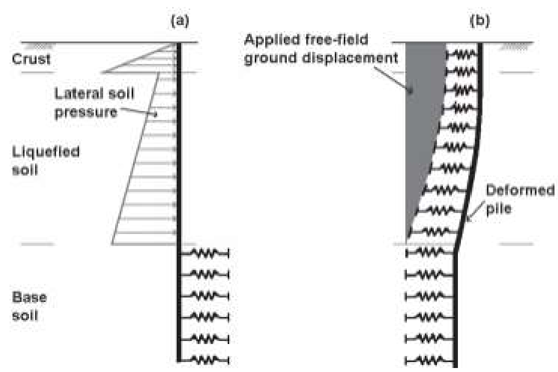


Surrey MUP Finite Element Model in SAP2000

All the elements in the structure were modeled as capacity protected (uncracked section properties) except the columns which were modeled as ductile (cracked section properties).

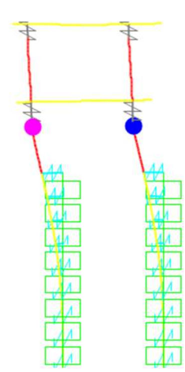
The following analysis models were used which consider p-y curves, response spectra and kinematic effects as recommended by the Geotechnical Engineer:

- Response spectra analysis: Linear global model with soil modelled using linear effective stiffness (manually iterated). Worst case of liquefied and non-liquefied response spectra curve was used for the design.
- Kinematic effects: Global model with soil modelled using nonlinear springs based on 'softened' p-y curves, crustal forces and kinematic displacements provided by the Geotechnical Engineer for this purpose.
    - Crustal forces were provided by the Geotechnical Engineer as distributed loads applied on the piles
    - Kinematic displacements were provided by the Geotechnical Engineer as displacement profiles (applied as ground displacements in SAP2000) below the crustal forces along the full length of the pile



Kinematic Effects

- Inelastic pushover analysis: Isolated pier models with soil modelled using nonlinear springs based on p-y curves provided by the Geotechnical Engineer. SAP2000 was used for inelastic static pushover analysis. The Concrete and steel strains at the plastic hinge region were calculated for the design displacement to ensure performance requirements are satisfied.



SAP2000 Inelastic Pushover Analysis Model of MUP3

5.5 Design & Detailing of Structural Components

The output from the SAP2000 analysis model was used to design the structural components. Most of the design was done in using Excel worksheets. However, S-Concrete was also used to verify the pier cap and column capacities.

The columns were designed as ductile elements. All the structural components were ensured to be capacity protected. Therefore, columns were detailed such that they can handle the displacement demands. Utmost care was taken to avoid rebar conflicts and congestion. All structural concrete elements have adequate rebar cover to ensure durability.

6 EXPANDED POLYSTYRENE (EPS) EMBANKMENT

Surrey MUP Structure terminates at the abutment, but Surrey MUP continues past the abutment. The soil in this area is settleable. To rule out any settlement concern, the embankment past Surrey MUP Structure Abutment is made on EPS instead of mineral fill. Since EPS embankment is constructed based on net zero additional pressure, the settlement concerns do not exist. This embankment connects to bridge road which marks the end of Surrey MUP.

7 DESIGN COMPLEXITY

Following elements added complexity to the design of Surrey MUP Structure:

- <u>IRREGULAR GEOMETRY</u>
  Irregular geometry of the structure resulted in amplified seismic force demands specially in the torsional modes which made design of the structural elements complicated and demanding.

- <u>LIQUIFIABLE & SETTLEABLE SOILS</u>
  Liquifiable soils resulted in adding kinematic forces which resulted in higher demands on lateral load resisting elements. Also, settleable soils introduced the need to use EPS foam embankment past the abutment to rule out any settlement which may have occurred if mineral fill were to be used instead.

- <u>CULTURAL & ENVIRONMENTAL CONSTRAINTS</u>
  Designing around the cultural and environmental constraints limited the flexibility of structural configuration. This also resulted in Surrey MUP Structure sharing piers with other adjacent structures

- <u>IMPACT OF OTHER STRUCTURES DUE TO PIER SHARING</u>
  Sharing piers with other adjacent structures introduced additional complexity in the design. Non-Linear Time history analysis was performed on the combined finite element model, which had all these structures, to determine the increased displacement demands for expansion joints at interaction locations of the adjacent structures with Surrey MUP.

- <u>PRELOADING IN THE PROXIMITY OF ABUTMENT</u>
  Preloading in the proximity of abutment may result in the increased down drag on the Abutment pile which means additional demand on pile foundation. The construction team has installed the inclinometers to measure this impact.

- <u>ELEVATION DIFFERENCE</u>
  Surrey MUP requires 12.5m of elevation drop from MUP1 Upper level to Abutment. When considering maximum allowed MUP finished surface gradient of 5%, such big drop in a limited space requires more winding spans in an archeologically and environmentally constrained space, thus causing complication in design.

- <u>CLEARANCE ENVELOPE</u>
  Surrey MUP Structure requires 4.0m clear width and 3.5m vertical clearance. As the Surrey MUP Structure is a two-level structure, the 3.5m vertical clearance constraint when considered with max. 5% finished surface gradient requirement added constraints to the height of the pier caps / girders which added complexity to the detailing of these structural elements.

- <u>DETAILING OF STRUCTURAL MEMBERS</u>
  Detailing of structural members, with limited room to increase its dimensions due to clearance requirement, to meet the increased design demands becomes difficult

8 CONSTRUCTION CHALLENGES

Following elements added challenges to the construction of Surrey MUP Structure:

- <u>CULTURAL & ENVIRONMENTAL CONSTRAINTS</u>
  There are locations of cultural importance in Surrey MUP Structure area which must remain undisturbed during construction. Additionally, there is Pattullo Creek which is environmentally sensitive and only allows very brief time window for instream construction activities. Working in such environment is like constructing in congested space where too many activities are happening in very limited space.

- <u>CONSTRUCTION IN CONGESTED SPACE</u>
  Construction in congested space requires extra vigilance to rule out safety concerns and mistakes. This impacts productivity.

- <u>PRELOADING IN TIGHT CONSTRUCTION SCHEDULE</u>
  Preloading soil near Surrey MUP Abutment requires significant time which adds to construction schedule in an area like Greater Vancouver Area known for poor weather conditions from construction point of view.

- <u>INTERFERENCE WITH EXISTING PATTULLO BRIDGE</u>
  The upper and lower levels of Surrey MUP from MUP3 ➔ SR1 cross a section of the existing Pattullo Bridge, which will require removal before construction of these spans. Hence, these spans will be done after the demolition of existing Pattullo Bridge.

- <u>INTERFERENCE WITH NEW HIGHWAY 17 EXIT RAMP BRIDGE</u>
  After construction, both levels of the Surrey MUP will pass under the Hwy 17 Exit Ramp at Pier SR1. This requires extra vigilance while constructing Surrey MUP Structure at this location (SR1).

- <u>EXISTING UTILITIES AND DRAINAGE</u>
  The existing drainage passes near pier Hwy 17 Exit Ramp shared Pier SR1 hence requires protection by the Contractor during construction. The existing municipal underground water pipe near Hwy 17 Exit Ramp shared pier SR2 will require relocation. All the other drainage and utilities under the embankment will be either relocated or protected.

- <u>UNEXPECTED GROUND CONDITIONS</u>
  During piling of Surrey MUP Structure, unexpected ground conditions encountered which caused refusal of pile driving to occur much deeper than anticipated. This required urgent sourcing of extra pile lengths to reach the pile refusal depth which was difficult.

- <u>POOR WEATHER CONDITIONS</u>
  Greater Vancouver Area is famous for a lot of rain which impacts construction schedule.

- HIGH GROUND WATER TABLE
  Ground water table is very close to ground surface in Surrey MUP Structure area. Though, the ground water table varies seasonally, it can impact construction if it is high at the time of construction.

9 CONCLUSION

In this paper, various components of the Surrey MUP were introduced which elaborated the factors contributing to the design complexity of this unusual structure. Some construction challenges were also discussed which are expected during the construction of Surrey MUP. All these efforts in design and construction will result in a structure which will meet the project functional requirements and facilitate the movement of pedestrians and cyclists, on the new bridge and to the Bridge Road below the new Bridge, for the next 100 years.

Acknowledgments

The authors acknowledge effort leading to the overall success of this paper:

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- American Association of State Highway and Transportation Officials (AASHTO), 2012. AASHTO LRFD Bridge Design Specifications, 8th Edition, Washington, D.C.
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