MMM Group Limited

CITY OF VANCOUVER

GEORGIA AND DUNSMUIR VIADUCTS LIMITED SEISMIC SCOPE STUDY FINAL REPORT

Project No. 5014103-003 | May 2015

COMMUNITIES

TRANSPORTATION

BUILDINGS

INFRASTRUCTURE

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STANDARD LIMITATIONS

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EXECUTIVE SUMMARY

At the request of the City of Vancouver (CoV), MMM Group Limited (MMM) has carried out a desktop review of the previous engineering work undertaken on discrete segments of the Georgia and Dunsmuir Viaducts for an assessment of the anticipated seismic deficiencies and order-of-magnitude cost estimate for the projected seismic retrofits required for the entire length of the Viaduct structures during an earthquake. Although the current code recommends a minimum performance of collapse prevention at 1 in 2475 year return earthquake for a new structure with an importance category of “Other” bridges, it recognizes that it may not be economically feasible to retrofit older structures to a degree of equivalence of a new bridge. Consistent with the previous reports and the retrofit strategies recommended in the Seismic Retrofit Design Criteria published by BC Ministry of Transportation and Infrastructure, this assessment was based on collapse prevention during a 1 in 475 year return earthquake. No additional seismic modelling or seismic analysis has been performed.

From the previous work done by Cochrane Engineering (the Cochrane Report 2004), and MMM Group (the MMM Report 2014), three major deficiencies were noted: (i) insufficient capacities of the foundations; (ii) lack of shear capacity and flexural ductility in pier columns; and (iii) insufficient anchorage of precast stringers into the pier cap beams. Since the area studied in the Cochrane Report is very representative of the remaining Viaducts, it is reasonable to expect that the rest of the Viaducts would behave similarly, except for different geotechnical risks as outlined in Thurber’s Geotechnical Report.

The following retrofit schemes are recommended to prevent collapse of the Viaducts during a 1 in 475 year return earthquake:

- Spread footing foundations: widening of concrete footing and addition of soil anchors
- Piled foundations: widening of concrete footing and addition of drilled shafts or jet grout columns, pending site specific constraints at each pier
- Fixed pier columns: use of elliptical steel jacket around the column to increase confinement and shear capacity
- Expansion pier columns: addition of an independent steel “catcher” frame on either side of the pier to prevent collapse of the superstructure
- Stringer-pier cap connection: install a steel bracket assembly to improve the connection between the concrete stringer and the pier cap beam.

Without detailed analysis or engineering design, it is anticipated that the order-of-magnitude capital cost estimate required to upgrade the Viaducts and their foundations to minimize the risk of collapse for the Georgia and Dunsmuir Viaducts be approximately $66 M. Given the limited scope in this review, a significant contingency of 35% is included in the estimated cost. This cost estimate is for budgetary purposes only. Should the CoV wish to refine the estimated cost with a reduced contingency, a detailed seismic analysis may be carried out.

Note that the proposed retrofit is for collapse prevention at 1 in 475 year return earthquake only and will not bring the Viaduct structures to today's standards for new bridge construction.

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1. INTRODUCTION

1.1 Background

The Georgia and Dunsmuir Viaducts were designed and constructed during the late 1960's and early 1970's to the code requirements of the day. The seismic design code requirements have changed drastically since that time and the City of Vancouver would like to have a review of the seismic performance of the Viaducts.

Seismic assessments have previously been carried out for portions of the existing Georgia and Dunsmuir Viaducts as part of works associated with adjacent building development projects. The two prevailing reports are:

- Conceptual Design Report – Seismic Assessment of the Georgia and Dunsmuir Viaducts by Cochrane Engineering (February 2004) prepared for Concord Pacific Group Inc. for the Costco Wholesale development (referred to as the "Cochrane Report" herein), and

- Georgia Viaduct Seismic Assessment Report by MMM Group (June 2014) prepared for Aquilini Development and Construction for the South Residential Tower (referred to as the "MMM Report" herein).

Each of the reports focuses on only isolated sections of the Viaducts: the Cochrane Report addresses the western most section of the Dunsmuir and Georgia Viaducts adjacent to Costco Wholesale building and the MMM Report addresses only the Georgia Viaduct sections around piers G18 to G20. See Figure 1 for the General Arrangement of the Viaducts, with highlights to sections studied in the previous reports.

Both of the Reports pointed out the risks associated with not addressing the Viaduct's seismic deficiencies, explicitly noting the consequences of potential collapse of the Viaducts onto the new developments. The Cochrane Report provides conceptual level seismic retrofit strategies for the west most portion of the Viaducts together with cost estimate of the capital work associated with this work in 2004 dollar value. The MMM Report does not explore the seismic retrofit strategies; it only addresses the viaduct seismic deficiencies in relation to Aquilini's proposed high-rise tower located adjacent to the Georgia Viaduct.

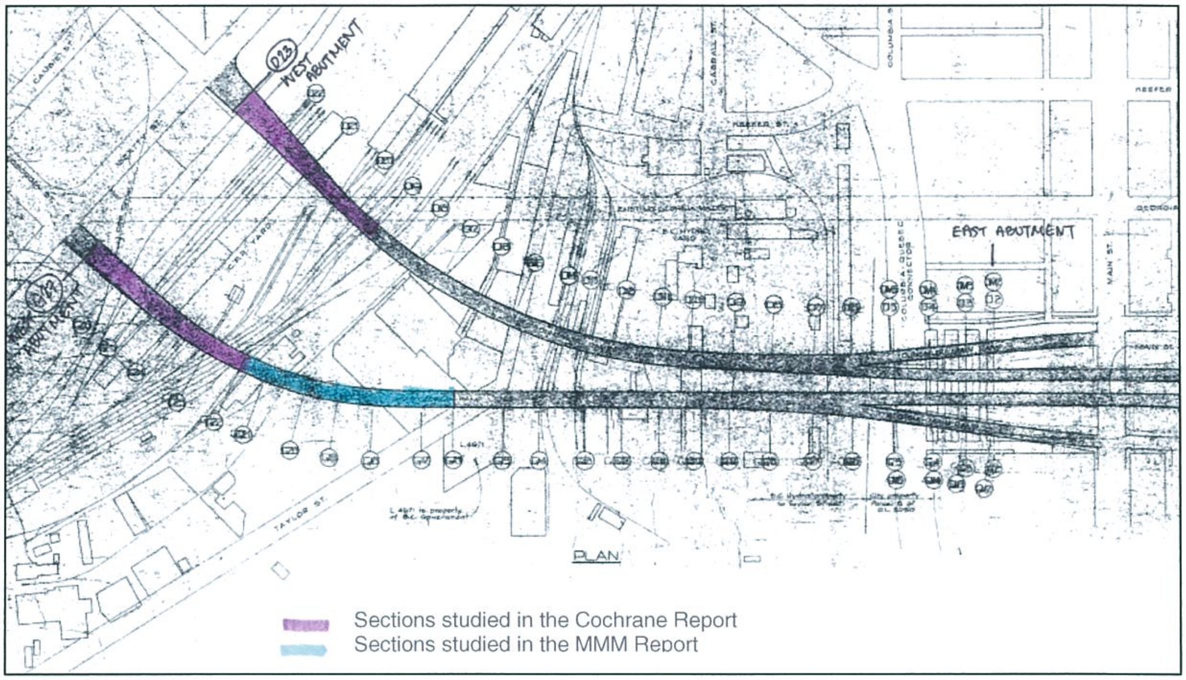

Figure 1. Viaducts General Arrangement

1.2 Scope of Work

This phase of work includes desktop review of the previous engineering work undertaken on discrete segments of the Viaducts to provide a high-level capital cost estimate required to upgrade the Viaducts and their foundations to minimize the risk of collapse. No additional seismic modelling or analysis is performed. In addition to the previous reports, the following documents are also reviewed:

- Record Drawings
- Vancouver Viaduct Study – Soil Quality Assessment by Golder Associates (2011)

The review of the anticipated seismic deficiencies for the entire length of the viaduct structures is only preliminary in nature and is based on our professional judgement, previous project experience, and extrapolation of the findings from the previous report's modeling and analysis. This phase also includes an order of magnitude capital cost estimate for the anticipated structural and foundation seismic retrofits by applying similar retrofit strategies, if deemed applicable, together with new retrofit concepts by MMM and Thurber to supplement those from the report. This report does not address the existing ground conditions beyond what was previously identified in those reports and general understanding of likely ground conditions inferred by professional geotechnical engineers.

2. SUMMARY OF PREVIOUS ANALYSIS FINDINGS

As a result of adjacent building development projects, portions of the Viaducts have been previously analyzed in detail for their seismic performance under the 1 in 475 year return period earthquake. The major findings from the two major analyses are summarized below.

2.1 The Cochrane Report (2004)

In 2004, Cochrane Engineering was retained by the City of Vancouver to assess the expected structural response and performance of the Viaducts during a potential seismic event in the vicinity of the new Costco development. The following outlines the key findings and recommendations from the Cochrane Report.

AREA STUDIED:

- West abutment of Georgia Viaduct to Pier # G22 and west abutment of Dunsmuir Viaduct to Pier # D19

PREVAILING DESIGN CODE AND PERFORMANCE CRITERIA

- CAN/CSA-S6-00
- Collapse Prevention at 1:475 year return design earthquake

ANALYSIS METHOD:

- Elastic Response Spectral Analysis for inertia load effect and force-based element capacities

RESULTS:

- Lack of flexural ductility in pier columns
- Shear failure in columns
- Insufficient anchorage of precast stringers into the pier cap beams (bottom flange)
- Insufficient lateral shear and uplift capacities of piled foundations
- Insufficient uplift and overturning capacities of spread footings as capacity-protected elements
- Acceptable estimated lateral displacement

RETROFIT STRATEGIES:

- Retrofit of pier columns to increase shear and flexural capacity
- Strengthen piled foundations with soil anchors
- Enlarge spread footing foundations
- Strengthen connection between bottom flange of precast stringers and the pier cap beam

- Estimated Cost for the portion of the Viaducts studied were: $630,000 and $490,000 for Dunsmuir and Georgia Viaducts, respectively (in 2004 dollar value)

2.2 The MMM Report (2014)

In 2014, Aquilini Development and Construction commissioned MMM Group Limited (MMM) to assess the impact of the proposed high rise development in close proximity to the Georgia Viaduct Piers G18 to G20. To understand the potential impact caused by the new development, MMM first analyzed the existing structure to create a 'base-case' scenario and the analyses were re-run with the new development in place (modifying the behavior for foundations at Piers G19 and G18). The following outlines the key points from the MMM Report.

AREA STUDIED:

- Georgia Viaduct from Pier G16 to G22

PREVAILING DESIGN CODE AND PERFORMANCE CRITERIA

- CAN/CSA-S6-06
- Evaluate seismic performance at 1:475 year return design earthquake

ANALYSIS METHOD:

- Elastic Response Spectral Analysis for inertia load effect and force-based element capacities
- Non-linear Analysis for effect of lateral spreading of soil due to liquefaction and force-based element capacities

RESULTS:

- New development has no adverse impact on the seismic performance of the Georgia Viaduct beyond the existing conditions and performance
- Deficiencies found (both before and after construction):
    - Lack of flexural ductility in pier columns
    - Shear failure in columns
    - Insufficient flexural and shear capacities of piled foundations

RETROFIT STRATEGIES:

- Not included in the scope

3. DESIGN EARTHQUAKE AND CURRENT CODE REQUIREMENTS

The governing bridge design code currently is the Canadian Highway Bridge Design Code CAN/CSA-S6-14, which was only recently published. The current code classifies bridges into three categories: Lifeline, Major-Route, and Other. As defined in the code, a Lifeline bridge is "large, unique, iconic, and/or complex structure that is vital to the integrity of the regional transportation network". Major-Route bridges, referred to as "Emergency-Route" bridges in previous editions of the code, are structures on or over a route that will be required to facilitate post-earthquake emergency response. Consistent with the assumptions in Cochrane Report, the Viaducts are not considered as lifeline or emergency route. The Viaducts are therefore assessed as "Other" bridges.

In accordance with the current code, new bridges that are classified as "Other" bridges are required to have the following minimum performance levels:

Seismic Ground Motion Probability of Exceedance in 50 years (return period)	Service	Damage
10% (475 years)	Service limited*	Repairable*
5% (975 years)	Service disruption*	Extensive*
2% (2475 years)	Life Safety	Probably replacement

*Optional performance levels unless required by the Regulatory Authority or the Owner.

As mentioned above, the performance requirements corresponding to the 475 year and 975 year return periods are optional. In other words, the minimum performance requirement for a new "Other" bridge structure is collapse prevention at 1 in 2475 year return earthquake. This performance requirement is more stringent than those considered in the previous Cochrane and MMM study, which was essentially collapse prevention during a 1 in 475 year return earthquake. The new code, however, recognizes that it may not be economically feasible to retrofit older structures to a degree of equivalence of a new bridge. The current retrofit policy outlined in the Seismic Retrofit Design Criteria, published by BC Ministry of Transportation and Infrastructure, only comprises upgrading to the 1 in 475 year return period event.

Given the limited scope in this current phase of the seismic review, the assessment and associated retrofit measures are for Life Safety at 1 in 475 year return earthquake only, which is consistent with the previous reports. This is considered the lowest level of performance for the lowest importance category of bridge structures. Regardless of the level of seismicity considered for structural performance, it is imperative that steps be taken to mitigate the seismic vulnerability of the Georgia and Dunsmuir Viaducts as the probability of these structures experiencing strong seismic shaking is quite high. A study by Tuna Onur and Mark Seemann conducted in 2004 determined the probability of "structurally" damaging ground shaking (MMI ≥ VII, PGA: 0.24g ± 0.07g) due to crustal or subcrustal earthquakes occurring within the next 50 years in Vancouver to be 12%. For the next phase of review, should the City wish to proceed, the desired seismic performance of the structures will be discussed and agreed upon with the City prior to carrying the detailed analysis and retrofit design. The City may wish to reconsider the importance category assigned to the Viaducts should the bridge usage be changed (for example, due to the potential relocation of St. Paul's Hospital). It should, however, be noted that it may be technically quite challenging and cost-prohibitive to have Immediate Service corresponding to a 475-year return period event in case the bridge category is changed to a Major-Route bridge.

4. STRUCTURE DESCRIPTION

The Georgia and Dunsmuir Viaducts, essentially parallel to each other, begin at Beatty Street to the west and continue over the Main Street Overpass to the east. The Dunsmuir Viaduct, located to the north, has 24 spans, whereas the Georgia Viaduct has 29 spans, including their ramps to Main Street at the east end.

The Viaducts are composed of multiple 2 and 3 span continuous structures. The superstructure comprises of composite cast-in-place concrete deck supported on precast I-shaped concrete stringers. The deck is typically 13.9 m wide (45.5 ft) with 6 lines of stringers. The deck is wider at the west end (up to 24 m with 9 lines of stringers), and narrower at the east end where it diverges into two separate on/off ramps of about 9 m wide with 4 lines of stringers each. The substructures of both Viaducts generally consist of single column cast-in-place concrete piers typically supported on piled foundations, except at the west end, where they are supported on spread footings. The pier columns are in the form of a "notched" rectangle (cruciform shape) with a flared column capital. The pier columns are "split" at the common interface between the continuous structures to accommodate for thermal movement.

5. GEOTECHNICAL CONSIDERATIONS

Thurber Engineering Ltd. (Thurber) has been retained to perform a desktop review of the ground conditions at the Viaduct sites and evaluate conceptual seismic retrofit requirements to address geotechnical risks at the Viaducts. Thurber concluded that the ground is highly liquefiable from the east abutment to around Pacific Boulevard to the west (between Piers G2 and G19 for Georgia Viaduct; and between Piers D2 to D19 for Dunsmuir Viaduct) and that drilled shafts or jet grouting would be required to prevent failure and provide lateral support to the existing piled foundations. The east approach embankment adjacent to the abutment at G2/GM2 and D2/DM2 would also require strengthening (such as jet grout columns) to reduce seismic deformation. Liquefaction potential is not considered high west of G19 and D19, and it is expected that the addition of soil anchors would be sufficient to strengthen the foundations for the design earthquake. It is estimated that the cost for geotechnical seismic retrofit measures would be about $14M for the Georgia Viaduct and $12M for the Dunsmuir Viaduct, including their associate ramps to Main Street. For further detail of the review and cost estimates carried out by Thurber, please see their report attached in Appendix A.

6. DEFICIENCIES EXTRAPOLATION AND RETROFIT STRATEGIES

Upon review of the General Arrangement As-Built Drawings, it is noted that the area studied in the Cochrane Report is very representative of the rest of the Viaducts. It covered:

- Both 2- and 3- span structures;
- Spread footing and piled foundations;
- Widest Deck width (up to 66 ft, with 9 lines of girders where typical deck is about 45.5 ft with 4 lines of girders);
- One of the tallest piers (36.8 ft, where the tallest pier along the length is about 37.2 ft); and
- Longest span length (up to 134 ft).

Therefore, without further analysis, it is reasonable to assume that the rest of the Viaducts would behave similarly as studied in the Cochrane Report, except for different geotechnical risks.

From both the Cochrane and MMM Reports, it is apparent that, at a minimum, the following retrofits would be required along the entire length of the Viaducts:

- Improve shear and flexure capacity of pier columns,
- Strengthen piled foundations,
- Widen spread footings; and,
- Strengthen the connection between precast stringers and pier cap beam.

In review of the retrofit scheme proposed in the Cochrane Report, the retrofit strategies need to be modified to create a more robust solution to achieve the performance required of today's design code and standards. Further details are discussed below for the various components.

6.1 Foundations

The Cochrane Report recommended that the spread footing be increased in size by about 1 to 1.5 m around the perimeter. From the Geotechnical Report, it is recommended that all spread footing foundations be strengthened with soil anchors. It is anticipated that, in order to form a reliable load path between new soil anchors and the existing spread footing, the footing should be increased all around the perimeter by at least 1.5 m and be doweled into the existing footing from the top as well. Where there is a column pedestal, the new concrete can tie into the pedestal. Where the pedestal is not present, the new concrete should extend to the column base with a 100 mm gap, so as not to interfere with column deformation.

For the piled foundations, Thurber recommended the addition of drilled shafts or jet grout columns, pending site specific constraints at each pier. Similar to the addition of soil anchors, the existing footings would need to be enlarged to tie-in the new drilled shafts or jet grout columns. It is anticipated that the footings would be enlarged by 2 m around the perimeter and be doweled into the existing footing from the top as well.

6.2 Pier Columns

For fixed pier columns, which are deficient in both shear and flexure, it is anticipated that the proposed addition of new concrete and shear reinforcement as presented in the Cochrane Report would not be sufficient to increase confinement and shear capacity of the pier columns. It is recommended that elliptical steel jacket be placed around the column to increase confinement and shear capacity. This is a very common and effective seismic retrofit method for non-circular columns used around the world for rectangular reinforced concrete columns with aspect ratio of less than 3.

For expansion pier columns, which are deficient in both shear and flexure, it is anticipated that the proposed addition of new concrete around the perimeter as presented in the Cochrane Report would not be sufficient to increase confinement and shear capacity of the expansion column. Given the existing geometry of the column, it is extremely difficult to increase its ductility and shear capacity in-situ. As an expansion column, the column is "split" in the middle to accommodate thermal movement of the superstructure. The gap between the "split" two halves ranges from ¾" to 1¾" wide. This gap is too narrow to allow for wrapping and/or casing the column to improve the confinement of the inside face of the column. It is impractical to provide confinement around the split column configuration without affecting the thermal movement capability of the column.

For the reasons noted above, we believe two options may be available for seismic retrofit of the expansion column:

1. Demolish and rebuild: This option involves temporarily supporting the superstructure while the column is being demolished and re-built. We believe this option is not economically feasible.

2. Superstructure Catcher System: Build a completely independent steel frame support system near the existing expansion pier columns which will only be engaged when the existing columns collapse. This is an effective solution which MMM has previously used for a BC Ministry of Transportation and Infrastructure project.

6.3 Stringer-Pier Cap Connection

According to the Cochrane Report, it is anticipated that the precast deck stringers are not sufficiently anchored into the pier cap beams and that an embedment failure of the bottom flange dowels that project into the pier cap beam can be expected. Steel bracket anchored to existing pier cap beam and bottom flange of stringer was proposed in the Cochrane's Report. Based on our review, it is anticipated that the proposed strategy is feasible, but the steel bracket anchorage system may need strengthening. Due to a limited scope at this stage, a high level cost estimate with contingency is used for each unit of steel bracket assembly required.

7. CLASS D CONSTRUCTION COST ESTIMATE

Based on the retrofit strategies discussed above, the order-of-magnitude capital cost for the structural and foundation seismic retrofits is summarized in the table below for each Viaduct. The estimated cost is based on a high level conceptual design without any detailed engineering analysis/design and is intended for budgetary purposes only. Note that as discussed, the retrofit measures are for collapse prevention of the Viaducts during a 1 in 475 year return earthquake only and after the proposed rehabilitation, the Viaducts may not be equivalent to a new structure designed to today's standard.

COST ESTIMATES – GEORGIA VIADUCT					
Items	unit cost	quantity		Total	
FOUNDATIONS					
foundation widening: FC	$1,200/m3	3400	m3	$ 4,080,000	

Geotechnical Work (total)	$14,000,000	1		$ 14,000,000	
PIER COLUMNS					
Elliptical Jackets for FC	$10/kg	340,500	kg	$ 3,405,000	
Concrete for FC	$600/m3	600	m3	$ 360,000	
Catcher Beam for EC	$50,000	20		$ 1,000,000	2 per EC
STRINGERS					
Steel Assembly for Connection	$10,000	344		$ 3,440,000	2/girder
Sub-total				$ 26,285,000	
Contingency – 35%				$ 9,199,750	
TOTAL				**$ 35,484,750**	

COST ESTIMATES – DUNSMUIR VIADUCT					
Items	unit cost	quantity		Total	
FOUNDATIONS					
foundation widening: FC	$1,200/m3	2800	m3	$ 3,360,000	
Geotechnical Work (total)	$12,400,000	1		$ 12,400,000	
PIER COLUMNS					
Elliptical Jackets for FC	$10/kg	280,000	kg	$ 2,800,000	
Concrete for FC	$600/m3	500	m3	$ 300,000	
Catcher Beam for EC	$50,000	18		$ 900,000	2 per EC
STRINGERS					
Steel Assembly for Connection	$10,000	284		$ 2,840,000	2/girder
Sub-total				$ 22,600,000	
Contingency – 35%				$ 7,910,000	
TOTAL				**$ 30,510,000**	

8. RECOMMENDATION

Should the City of Vancouver wish to refine the estimated cost with a reduced contingency, a detailed seismic analysis may be carried out for the Viaducts to better understand the performance of the structure and develop a conceptual design level seismic retrofit.

Prepared By	Reviewed By	Approved By
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APPENDIX A – GEOTECHNICAL REPORT

THURBER ENGINEERING LTD.

May 13, 2015 File: 19-5161-260

MMM Group
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Attention: Caroline Ngan, P. Eng.
Project Engineer, Bridges

GEORGIA AND DUNSMUIR VIADUCTS
SEISMIC ASSESSMENT TO DETERMINE CONCEPTUAL SEISMIC RETROFIT MEASURES
GEOTECHNICAL INPUT

Dear Caroline:

As requested, this letter summarizes Thurber Engineering Ltd. (Thurber)'s high-level geotechnical input into an initial seismic assessment of the Georgia and Dunsmuir Viaducts, particularly focussed on conceptual seismic retrofit requirements to address geotechnical issues. The assessment was completed for both viaducts including the east approach embankment and the Main Street ramps but excluded the Main Street Overpass and approach embankments (the east approach embankment for the viaducts is a common approach fill and is continuous with the west approach embankment for the Main Street Overpass).

It is a condition of this letter that Thurber's performance of its professional services is subject to the attached Statement of Limitations and Conditions.

1. INTRODUCTION

The Georgia and Dunsmuir Viaducts are multi-span structures that carry eastbound and westbound traffic, respectively, between Georgia Street at Beatty Street and Prior Street at Gore Avenue. Westbound on and eastbound off-ramps are located about 700 m east of Beatty Street which tie into Main Street (Main Street ramps). Figure 1 shows the historic test hole locations relative to the approximate pier locations.

The geotechnical assessment was limited to a desktop review of geotechnical information provided by MMM and from Thurber's past experience in the area. The information reviewed was as follows:

- "Preliminary Environmental Evaluation: Vancouver Viaduct Study Soil Quality Assessment", by Golder Associates, September 22, 2011
- "Conceptual Design Report – Seismic Assessment of the Georgia and Dunsmuir Viaducts", Cochrane Engineering (Cochrane), 2004
- "Georgia Viaduct Seismic Assessment Report", by MMM Group, June 2014
- "Georgia Viaduct Replacement" electronic pdf copies of as-built drawings of the Georgia and Dunsmuir Viaduct from the late 1960's to early 1970's

- "Georgia Street Ramp and Steps – Preliminary Geotechnical Evaluation" by Thurber Engineering, August 21, 2014

Detailed geotechnical analysis was not included within the current scope of work. The geotechnical assessment was based on engineering judgement and our experience with similar seismic retrofit projects.

2. SOIL AND GROUNDWATER CONDITIONS

The Geological Survey of Canada surficial geology map of the area indicates that both viaducts are situated over till-like soil along the west and east extents which forms the slopes adjacent to False Creek. The central portion of the viaducts are situated on reclaimed land along the north side of False Creek. Figures 2a and 2b respectively show annotated geologic profiles along the Georgia and Dunsmuir Viaduct alignments which were obtained from as-built drawings. In general, a relatively thin layer of fill overlying till-like soil is present at the east and west end of the viaduct alignments while random fill overlying marine silt / clay underlain by till-like soil is present through the central portion of the viaduct alignments. The depth to till-like soil varies from 8 to 14 m through the central portion of the Georgia Viaduct while the depth to till-like soil varies from 8 to 11 m through the central portion of the Dunsmuir Viaduct.

The penetration resistance at various depths, which were assumed to be energy-corrected SPT N-values for the purposes of this assessment, are noted beside the borehole logs on the as-built drawings. Higher N-values are noted where there is minimal to no soft silt / clay soil below the fill whereas the N-values are generally low where fill is underlain by soft silt / clay deposits. This suggests that the fill used to reclaim the north side of False Creek was likely placed with limited compactive effort.

Groundwater levels in the area are anticipated to be heavily influenced by tidal fluctuations in False Creek. For the purposes of this assessment, we estimate that the water table is at about El. 0 m (estimated to be approximately El. 92' on Figure 2a and 2b).

3. HIGH-LEVEL GEOTECHNICAL SEISMIC ASSESSMENT

3.1 General

For the purposes of this assessment, the 1 in 475 year return period earthquake was used as the design earthquake with a 'life safety' performance requirement, consistent with the 2006 version of the Canadian Highway Bridge Code Design Code (CHBDC). It should be noted that the recently released 2015 version of CHBDC has moved toward a 'life safety' performance requirement using the 1 in 2475 year return period earthquake. The potential for liquefaction triggering of the soil below and in the vicinity of viaducts during the design earthquake was assessed qualitatively using engineering judgement and experience on similar projects.

To determine appropriate conceptual seismic retrofit measures including ground improvement requirements, the potential for soil strength loss and the associated impacts on both inertial response and the potential for kinematic loading of foundations were considered.

3.2 Methodology

To determine conceptual seismic retrofit measures, the performance of each pier was assessed relative to the retrofit concept presented in Cochrane's 2004 report, which was designated the "base case retrofit" option. Cochrane's assessment was conducted for a section of the Georgia Viaduct between the west abutment and pier G22 and the Dunsmuir Viaduct between the west abutment and pier D19. The foundations within Cochrane's area of assessment comprise the following:

- Georgia Viaduct between the west abutment and pier G22 – spread footings founded on compact to dense fill and / or dense till-like soil
- Dunsmuir Viaduct between the west abutment and pier D19 – spread footings founded on compact to dense fill and / or dense till-like soil and pile foundations comprised of H-Piles and expanded base piles.

Cochrane's recommended retrofit comprised soil anchors installed through the footing / pile cap to address overturning and inertial loading issues. Cochrane's report did not appear to assess the impact of liquefaction or strain softening on lateral resistance of the piled foundation below the Dunsmuir Viaduct.

MMM's June 2014 assessment was completed for the Georgia Viaduct at piers G16 to G20. The assessment included an evaluation of issues associated with liquefaction and strength loss of soil surrounding the pier foundations but did not include consideration of retrofit measures. However, MMM's assessment provides an indication of foundation performance when liquefaction is triggered.

Based on the above, Thurber completed the assessment of conceptual geotechnical retrofit measures using the following methodology:

- Review soil conditions at each pier location relative to soil conditions used Cochrane's "base case retrofit" assessment. Where piers are located between borehole locations, an interpolated soil profile was assumed.
- Identify the potential for liquefaction and / or strain softening of the soil at and in the vicinity of each pier and abutment foundation.
- Identify the potential for kinematic loading on foundations due to soil deformation at each pier and abutment.
- Identify conceptual retrofit options, including ground improvement.

We understand the structural evaluation completed by MMM as part of this study has identified some piers that were designed as expansion columns which are very difficult to retrofit.

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Consideration is being given to the use of an independent support system (a steel "catcher" frame system) at these piers.

3.3 Geotechnical Assessment

A summary of the assessment results for the Georgia and Dunsmuir Viaducts, including the Main Street ramps, are tabulated in Figures 2a and 2b, respectively. The table includes the following:

- The existing foundation type (spread footing, expanded base piles, H-Piles or timber piles)
- Assessment of performance relative to the "base case retrofit" option
- Assessment of the potential for liquefaction / strain softening
- Assessment of the potential for kinematic loading on foundations due to soil deformation
- Conceptual geotechnical retrofit measures (discussed in Section 3.4)

Loose fill encountered below the groundwater table with N-values of 15 or less is likely to be liquefiable during the design earthquake. The soft silt / clay deposit encountered between piers G2 to G19, GM3 to GM5, D2 to D19 and DM2 to DM5 are likely to be susceptible to strain softening under the design earthquake. Figures 2a and 2b provides additional details on where liquefaction / strain softening is anticipated.

It is not clear if piers G26 and G25 comprise spread footings or pile foundations due to discrepancies in the as-built drawings. For the purposes of this assessment, it was assumed the piers are supported on spread footings. Based on the anticipated soil conditions, the foundation type will not influence the recommended conceptual retrofit measures at these piers.

The pile toe elevations for piers G2 to G20, GM2 to GM5, D2 to D20 and DM2 to DM5 were not shown on the as-built drawings. However, the drawings specified that the piles were to extend to the till-like soil. Consequently, it was assumed that all pile foundations were completed / driven into till-like soil based on the depth to till-like soil shown on Figures 2a and 2b.

The Main Street ramps start at Piers D6 and G6 where there are separate foundations and columns for the mainline and ramp but a shared pier cap and continuous deck. For the purposes of this assessment, it was assumed that both the mainline and ramp foundations at these piers required retrofitting, regardless of whether the Main Street ramps will ultimately be included in the retrofit or not.

3.4 Conceptual Seismic Retrofit Requirements

3.4.1 General

The high-level conceptual seismic retrofit options presented below were developed to guide future evaluations and provide input to Class D construction cost estimates. Figures 2a and 2b summarize the recommended conceptual retrofit requirements at each pier and abutment. The various requirements are described in further detail below.

3.4.2 East Approach Embankment Adjacent to Pier G2/GM2 and D2/DM2

At the east approach embankment adjacent to piers G2, GM2, D2 and DM2, deformation of the approach embankment is anticipated and the deformation will result in large kinematic loads on these foundations. Due to the approach embankment height, kinematic loads are expected to be sufficiently high that designing foundation elements to resist the kinematic loads will likely be problematic. Accordingly, we recommend conceptual retrofit measures in the vicinity of the east approach embankment include jet grout columns to improve foundation strength and reduce seismic deformation. Jet grout columns forming a U-shaped block around the piers and abutments, similar to a seismic dike, is recommended as shown on Figure 3. Additional retrofit measures for the pier foundations are also required and discussed below. The concept shown on Figure 3 assumes the retrofit of each viaduct will be completed independently and kinematic loading on the Main Street ramps must be address. If the retrofit were to be completed on both viaducts concurrently and the Main Street ramps were excluded from the retrofit, the amount of jet grouting could be reduced by about 30%.

3.4.3 Piers G2 to G18, GM2 to GM5, D2 to D18 and DM2 to DM5

At piers G2 to G18, GM2 to GM5, D2 to D18 and DM2 to DM5, till-like soil is relatively deep and liquefiable soil layers are present. At these piers the potential for buckling and/or loss of lateral support is a major issue for smaller sized retrofit measures such as the anchors proposed in Cochrane's "base case retrofit". To address buckling and/or loss of lateral support, the following are considered feasible retrofit options:

- Option 1 - drilled shafts
- Option 2 - jet grout ground improvement.

Given the significant amount of existing infrastructure in the area, it is likely that different options will be necessary at different piers depending on site specific constraints.

We understand that MMM's June 2014 assessment identified the potential for lateral spread due to liquefaction. The magnitude of lateral spreading has not been assessed for this desktop study. Based on the relatively flat topography in the vicinity of the viaducts and approximate 150 m distance from False Creek, we do not anticipate ground displacements due to lateral spreading to be significant away from the east approach embankment. Nonetheless the retrofit options above should be sufficiently robust to resist kinematic loading at the pier locations if lateral spreading does occur.

The use of stone column or timber compaction piles are other methods of ground improvement commonly used for seismic retrofits but are not considered appropriate for the viaducts. The use of stone columns or timber compaction piles to mitigate liquefaction will not improve the pile to pile cap connection, which is required in this case. Additional issues associated with the use of

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stone columns or timber compaction piles include the potential for vibration and/or lateral soil displacement related damage to surrounding structures, including the bridge. Stone columns are also problematic where soil and groundwater contamination is present due to the potential for migration of contamination through the stone columns.

<u>Option 1 - Cast-in-Place (CIP) Drilled Shafts</u>

For this option, four drilled shafts at each pier are contemplated, one on each side of the foundation. The drilled shafts would need to be extended into till-like soil on the order of 5 to 10 diameters to achieve lateral fixity. The drilled shafts would need to be on the order of 1.2 to 1.8 m diameter to resist lateral loads imposed under inertial loading with liquefied soil conditions. Where drilled shaft installation in limited access or restricted headroom conditions is required, there will be a cost premium associated with construction. Spoils from drilled shaft installation where soil and groundwater contamination is present may require special disposal measures which could increase costs.

<u>Option 2 - Jet Grout Columns</u>

A jet grout retrofit option would comprise installation of a ring of jet grout columns around each pier foundation. The jet grout column ring would be designed to form a caisson-type foundation. The jet grout columns would be reinforced with steel I-beams to provide lateral resistance and to allow the jet grout ring to be structurally connected to the pile cap. The jet grouting can easily be installed in low headroom conditions and would provide an essentially new foundation support system. The disadvantage of jet grouting would be the challenges associated with spoils management in a congested area. Jet grouting spoils where soil and groundwater contamination is present may also require special disposal measures which could increase costs. The use of jet grouting for pier retrofits is considered less reliable than the use of drilled shafts.

3.4.4 Piers G19 to G26 and D19 to D22

At piers G19 to G26 and D19 to D22 till-like soil is relatively shallow and the use of soil anchors consistent with Cochrane's "base case retrofit" is considered the most reasonable retrofit option. Soil anchors would be installed in both the longitudinal and transverse direction to resist inertial loads on the foundations. Soil anchors are generally not considered feasible where liquefiable soil layers more than about 3 m thick are present due to the potential for buckling and/or loss of lateral support. From an installation perspective, soil anchors are relatively simple given the ability to use small equipment. A key consideration related to soil anchors is the complex layout geometry with installation of inclined anchors and the potential for conflicts when coring through the pile cap and / or utility conflicts.

Soil conditions at Piers G19 and G20 and D19 and D20 are transitional. Soil anchors are still considered feasible but may require additional anchors with permanent casing to address buckling and loss of lateral support. Although piers D19 and D20 were part of Cochrane's study, Table 2b identifies its performance relative to the "base case retrofit" as being worse due to the potential of strain softening of silt / clay layer at depth and possible liquefaction which wasn't considered in Cochrane's report.

3.4.5 West Abutment

The west abutment of both structures are founded on competent till-like soil and retrofit measures are not anticipated from a geotechnical perspective.

3.4.6 Catcher Frame System

The "catcher" frame system being considered at the expansion columns will be designed to support the superstructure in the event of failure of the column under the design seismic event. Where depth to till-like soil is relatively deep, the foundations for the proposed system will likely need to comprise drilled shafts or jet grout columns as described above and the design is estimated to be similar to the geotechnical retrofit design case.

Where the depth to till-like soil is relatively shallow, it is feasible from a geotechnical perspective to place the foundations of the "catcher" frame on spread footings founded on till-like soil. However, spread footings may not work from a structural perspective as well as logistically due to property and utility constraints. As such, the "catcher" frame system may need to be supported by drilled shafts installed 7 to 10 diameters into the till-like to achieve lateral fixity. However, as till-like soil is closer to surface, the total length of the drilled shaft will likely be governed by lateral fixity considerations.

4. CLASS D CONSTRUCTION COST ESTIMATE

Class D construction cost estimates for the geotechnical seismic retrofit measures discussed above are provided in the table below.

The cost for shorter drilled shafts completed in till-like soil for the "catcher" support system at G19 to G26 and D19 to D22 is estimated to be comparable to the cost to install all the soil anchors at the same location.

Element	Geotechnical Retrofit Option	High-Level Cost
Georgia Viaduct		
East Approach Fill	Jet Grout Seismic Dike	$1.3 million
Piers G2 to G18	Option 1: Drilled Shafts Option 2: Jet Grout Columns	$9.4 million (Drilled Shafts) $7.8 million (Jet Grout Columns)
Piers G19 to G26	Soil Anchors / Drilled Shafts for "catcher" foundation	$1.3 million
West Abutment	Not Anticipated	N/A
Dunsmuir Viaduct		
East Approach Fill	Jet Grout Seismic Dike	$1.3 million
Piers D2 to D18	Option 1: Drilled Shafts Option 2: Jet Grout Columns	$8.4 million (Drilled Shafts) $5.6 million (Jet Grout Columns)
Piers D19 to D22	Soil Anchors / Drilled Shafts for "catcher" foundation	$0.7 million
West Abutment	Not Anticipated	N/A
Main Street On/Off Ramps		
Piers GM2 to GM5 and DM2 to DM5	Option 1: Drilled Shafts Option 2: Jet Grout Columns	$4.0 million (Drilled Shafts) $2.4 million (Jet Grout Columns)

We trust that this information is sufficient for your needs. Should you require clarification of any item or additional information, please contact us at your convenience.

Yours truly,
Thurber Engineering Ltd.
Paul Wilson, P. Eng.
Review Principal

May 13, 2015

May 13/15

Denny Ma. P. Eng.
Project Engineer

Attachments: Statement of Limitations and Conditions
Figure 1 – Historic Test Hole and Approximate Pier Location Plan
Figure 2a – Interpreted Geologic Section along Georgia Viaduct
Figure 2b – Interpreted Geologic Section along Dunsmuir Viaduct
Figure 3 – Conceptual Jet Grout Plan Area for East Approach Fill

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a) Nature and Exactness of Soil and Contaminant Description: Classification and identification of soils, rocks, geological units, contaminant materials and quantities have been based on investigations performed in accordance with the standards set out in Paragraph 1. Classification and identification of these factors are judgmental in nature. Comprehensive sampling and testing programs implemented with the appropriate equipment by experienced personnel may fail to locate some conditions. All investigations utilizing the standards of Paragraph 1 will involve an inherent risk that some conditions will not be detected and all documents or records summarizing such investigations will be based on assumptions of what exists between the actual points sampled. Actual conditions may vary significantly between the points investigated and the Client and all other persons making use of such documents or records with our express written consent should be aware of this risk and the Report is delivered subject to the express condition that such risk is accepted by the Client and such other persons. Some conditions are subject to change over time and those making use of the Report should be aware of this possibility and understand that the Report only presents the conditions at the sampled points at the time of sampling. If special concerns exist, or the Client has special considerations or requirements, the Client should disclose them so that additional or special investigations may be undertaken which would not otherwise be within the scope of investigations made for the purposes of the Report.

b) Reliance on Provided Information: The evaluation and conclusions contained in the Report have been prepared on the basis of conditions in evidence at the time of site inspections and on the basis of information provided to Thurber. Thurber has relied in good faith upon representations, information and instructions provided by the Client and others concerning the site. Accordingly, Thurber does not accept responsibility for any deficiency, misstatement or inaccuracy contained in the Report as a result of misstatements, omissions, misrepresentations, or fraudulent acts of the Client or other persons providing information relied on by Thurber. Thurber is entitled to rely on such representations, information and instructions and is not required to carry out investigations to determine the truth or accuracy of such representations, information and instructions.

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d) Construction Services: During construction Thurber should be retained to provide field reviews. Field reviews consist of performing sufficient and timely observations of encountered conditions in order to confirm and document that the site conditions do not materially differ from those interpreted conditions considered in the preparation of the report. Adequate field reviews are necessary for Thurber to provide letters of assurance, in accordance with the requirements of many regulatory authorities.

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Plotted: April 30, 2015

LEGEND:

- TEST HOLE LOCATION
- PIER LOCATION
- SEISMIC ASSESSMENT STUDY LIMITS

NOTES:

1. AERIAL IMAGE SHOWN TAKEN FROM THE CITY OF VANCOUVER'S OPEN DATA CATALOGUE FILE "city_vancouver_utm10_2011".
2. TEST HOLE AND PIER LOCATIONS ARE APPROXIMATE BASED ON AS BUILT DRAWINGS

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CLIENT	MMM GROUP
	HISTORIC TEST HOLE AND APPROXIMATE PIER LOCATION PLAN
	GEORGIA VIADUCT SEISMIC ASSESSMENT — VANCOUVER, BC
SEAL	

DESIGNED	DRAWN	APPROVED
DM	NAK	PJW
DATE		SCALE
APRIL 30, 2015		AS SHOWN
PROJECT No.	FIG. No.	REV.
19-5161-260	1	-

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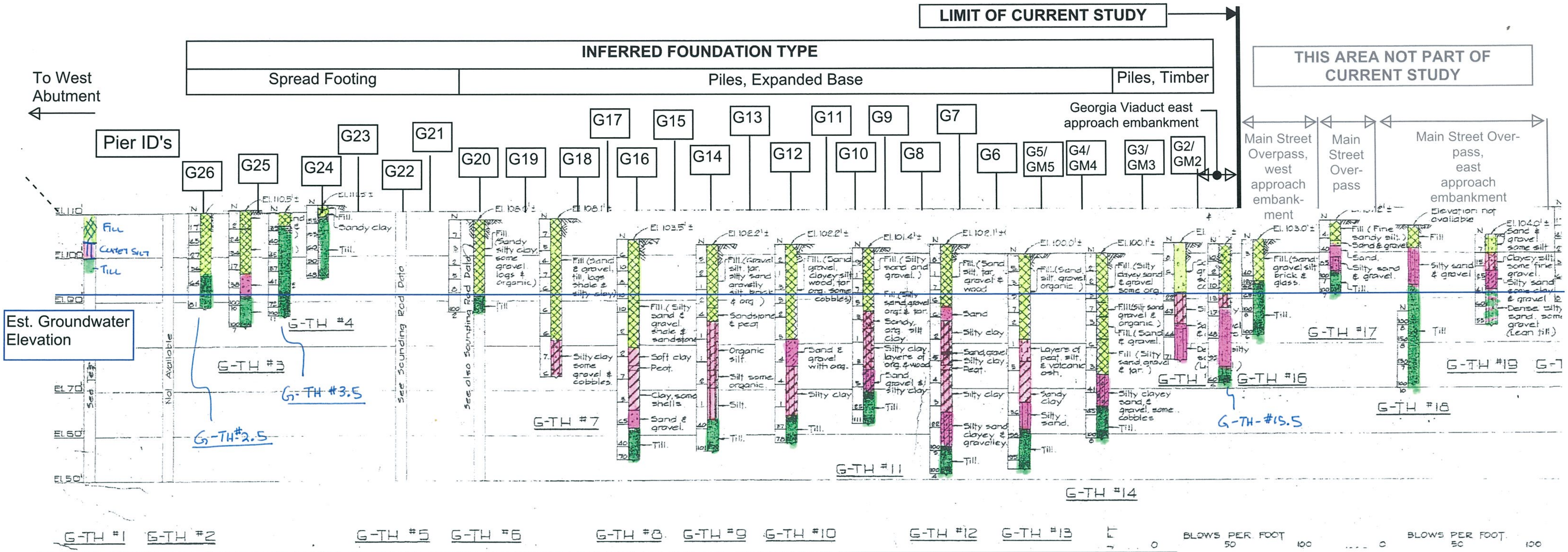
CANCEL PRINTS BEARING EARLIER LETTER



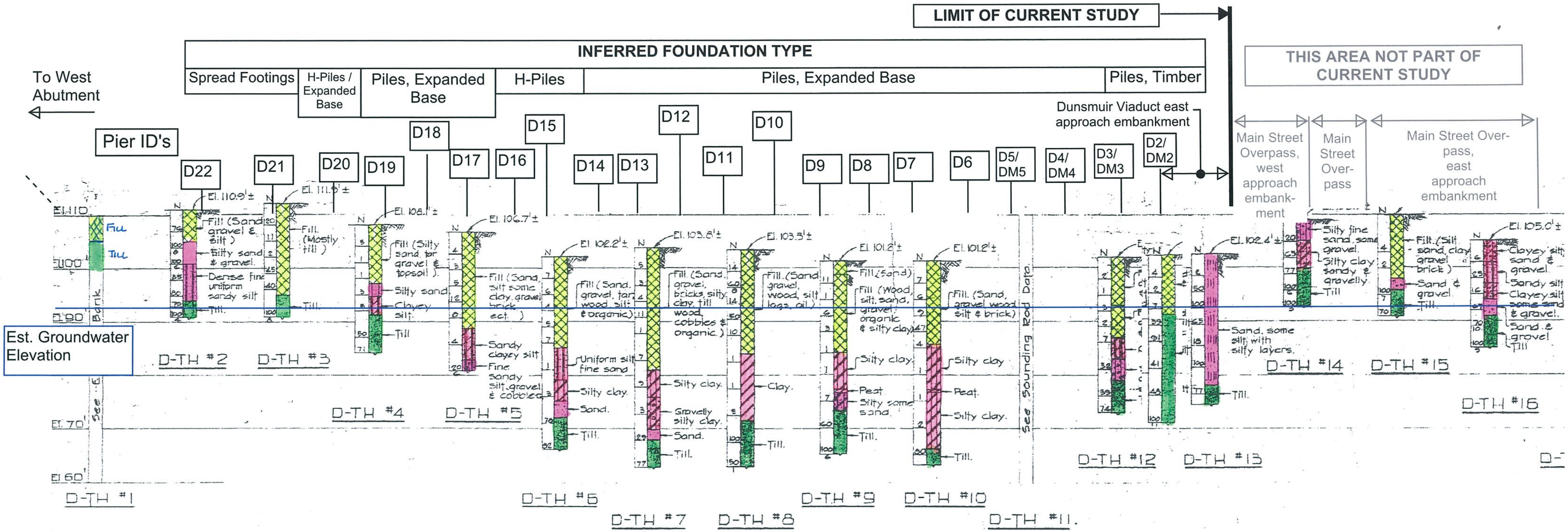
Pier ID	Performance relative to Base Case Retrofit Scenario*	Liquefaction / Strain Softening	Kinematic Loading Issue	Conceptual Seismic Retrofit Options	Pier ID	Performance relative to Base Case Retrofit Scenario*	Liquefaction / Strain Softening	Kinematic Loading Issue	Conceptual Seismic Retrofit Options
West Abutment	Better	Not Likely	Not Likely	None anticipated	G13	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
G26	Similar	Not Likely	Not Likely	Soil Anchors	G12	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
G25	Similar	Not Likely	Not Likely	Soil Anchors	G11	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
G24	Similar	Not Likely	Not Likely	Soil Anchors	G10	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
G23	Similar	Not Likely	Not Likely	Soil Anchors	G9	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
G22	Similar	Not Likely	Not Likely	Soil Anchors	G8	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
G21	Similar	Not Likely	Not Likely	Soil Anchors	G7	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
G20	Worse	Likely	Not Likely	Soil Anchors	G6	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
G19	Worse	Likely	Not Likely	Soil Anchors	G5/GM5	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
G18	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting	G4/GM4	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
G17	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting	G3/GM3	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
G16	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting	G2/GM2	Worse	Likely	Likely	Drilled Shafts or Jet Grouting
G15	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting	East Approach Embankment	Worse	Likely	Likely	Jet Grouting (Seismic Dike) **See Figure 3**
G14	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting					

*Note: Base Case Retrofit Scenario is based on Cochrane Engineering's recommended soil anchors for spread footings founded on fill and/or till-like soil

LEGEND

- FILL
- SILT / CLAY / ORGANIC SOIL
- SILTY SAND / SAND + GRAVEL
- TILL-LIKE SOIL

FIGURE 2A - Interpreted geologic profile along Georgia Viaduct alignment and approximate pier locations and foundation type. Summary of conceptual geotechnical seismic retrofit measures tabulated as shown



Pier ID	Performance relative to Base Case Retrofit Scenario*	Liquefaction / Strain Softening	Kinematic Loading Issue	Conceptual Seismic Retrofit Options	Pier ID	Performance relative to Base Case Retrofit Scenario*	Liquefaction / Strain Softening	Kinematic Loading Issue	Conceptual Seismic Retrofit Options
West Abutment	Better	Not Likely	Not Likely	None anticipated	D11	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
D22	Similar	Not Likely	Not Likely	Soil Anchors	D10	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
D21	Similar	Not Likely	Not Likely	Soil Anchors	D9	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
D20	Worse	Likely	Not Likely	Soil Anchors	D8	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
D19	Worse	Likely	Not Likely	Soil Anchors	D7	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
D18	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting	D6	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
D17	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting	D5/DM5	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
D16	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting	D4/DM4	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
D15	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting	D3/DM3	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting
D14	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting	D2/DM2	Worse	Likely	Likely	Drilled Shafts or Jet Grouting
D13	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting	East Approach Embankment	Worse	Likely	Likely	Jet Grouting (Seismic Dike) **See Figure 3**
D12	Worse	Likely	Not Likely	Drilled Shafts or Jet Grouting					

*Note: Base Case Retrofit Scenario is based on Cochrane Engineering's recommended soil anchors for spread footings founded on fill and/or till-like soil

LEGEND

- FILL
- SILT / CLAY / ORGANIC SOIL
- SILTY SAND / SAND + GRAVEL
- TILL-LIKE SOIL

FIGURE 2B - Interpreted geologic profile along Dunsmuir Viaduct alignment and approximate pier locations and foundation type. Summary of conceptual geotechnical seismic retrofit measures tabulated as shown

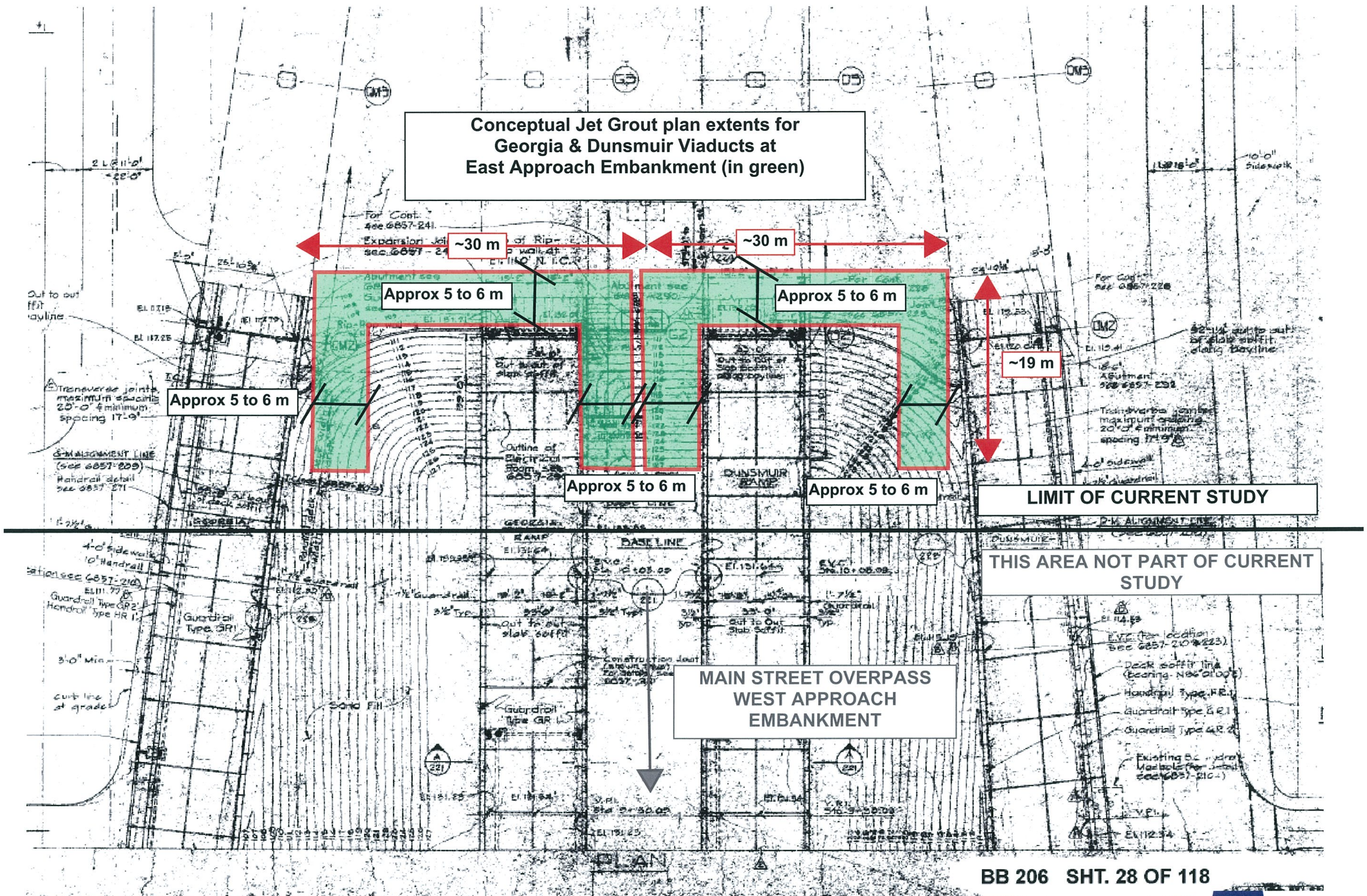


FIGURE 3 - Conceptual Jet Grout Plan Area (in green) for Georgia & Dunsmuir Viaducts at East Approach Embankment