Canadian Conference - Pacific Conference on Earthquake Engineering 2023
Vancouver, British Columbia
June 25th – June 30th, 2023

Performance review of 1st bridge retrofitted in BC

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ABSTRACT

Queensborough was the first bridge ever retrofitted in BC. 01553 Queensborough Bridge (the Bridge) is constructed in 1960 and contains multiple segments. The Main Span segment (01553B) consists of three continuous spans of haunched steel plate girders with a total length of 205 m. The South Approach segment (01553A) consists of twenty-five concrete girder spans, built as a series of 3 span continuous, with a total length of 384 m. The North Approach segment (01553C) consists of nine concrete girder spans with a total span length of 183 m. In 1984, the six cast-in-place approach spans south of Bent S23 were replaced with pre-stressed concrete I-girder, reducing the number of spans by two while adding a curved alignment and a new south abutment.

The Bridge received a seismic retrofit, including ground improvements, to the Safety Level in the 1990s. Key upgrades include encasing the column base with steel jackets, installing seismic restrainers at expansion joints, post tensioning diaphragms at Bents S8 to S3, installing new elastomeric bearings directly above the columns, and replacing the Main Span rocker bearings with rubber and lead rubber isolation bearings at the two main Piers. The Bridge was also modified as a part of the Border Infrastructure Program in 2005, which included widening of the North Approach to improve the turning radius and better accommodate heavy vehicle traffic. The deck widening was achieved by adding a new precast box girder on the east edge of the bridge from Bent N5 to Bent N11 and removing two end spans.

In this paper the effect of the original retrofit strategies is assessed on the behavior of the bridge to understand how effective the strategies are with the elevated seismic demands and desired seismic performance based on the current code. A discussion is made on the strategies which could make the structure most resilient against the prospect larger earthquakes; in the other word, the strategies that most decouples the behavior of the structure from the seismic demand magnitude.

Keywords: Seismic Retrofit, Bridge Design, Seismic Retrofit of Bridges, Seismic Performance assessment, Seismic Design

INTRODUCTION

The Canadian Highway Bridge Design Code (CHBDC S6-14) has updated its hazard levels to 1:475 AEP, 1:975 AEP and 1:2475 AEP (probability of exceedance of 10%,5% and 2% in 50 years) and enhanced the performance objectives in comparison with the prior revisions (i.e. 1995 revision which the Bridge was retrofitted to). The Ministry intended to understand the current performance of the structure based on the updated hazard levels. It is also of interest to evaluate the amount of retrofit effort required to upgrade the structure performance to the current code performance objectives.

The Ministry has retained Mott MacDonald to assess the seismic performance of the existing structure to identify the performance level of the structure based on (CHBDC S6-14) and (Supplement to CHBDC S16-14, 2016).

The assessment began with a desktop review of the existing documents to understand the original design, history of modifications, seismic retrofits, functional upgrades and the current condition of the Bridge. Following the review of previous structure modifications, the criteria to which the structure was retrofitted was extracted from the seismic retrofit report (Sandwell, 1995). To update our understanding of the site's geotechnical issues and to obtain the current site specific spectra, Golder Associates LTD. was engaged by the Ministry. The seismic hazard levels to which the structure was retrofitted in 1993 is compared to the current code seismic hazard levels. Seismic hazards for our current assessment was developed based on (CHBDC S6-14, 2014) and (Supplement to CHBDC S16-14, 2016) seismic performance objectives.

As an initial evaluation of the seismic performance of the structure, selected bents have been analyzed considering the retrofits implemented.. Displacement ductility and force-based capacities of the elements are Calculate and the vulnerable elements are identified.

The preliminary seismic assessment was limited to an isolated bent RSA and ISPA undertaken on one Main Span bent (S1) and one South Approach bent (S4). As the assessment is high level, the selected bents are not necessarily representative of the whole structure and the seismic behaviors described in this paper may vary on other bents.

BRIDGE DESCRIPTION

The 01553 Queensborough Bridge consists of the five segments shown in Error! Reference source not found. and described below from left to right.

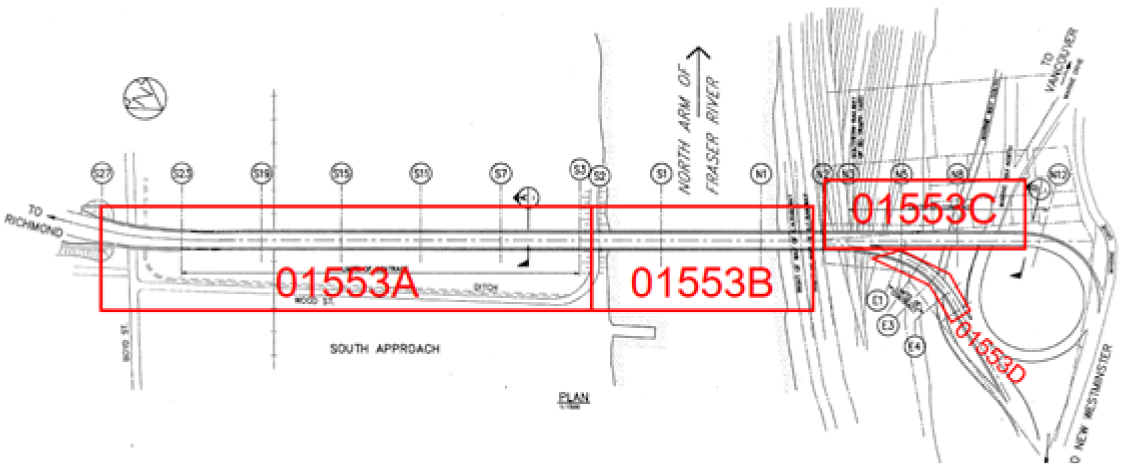

Figure 1: Bridge Segments

Structure 01553A – The South Approach spans Pier S27 to S2

4 spans (S27 to S23) Built in 1984, with a total segment length of 73 m are supported by nine or ten pre-stressed, pre-cast concrete I girders. The substructure consists of a two-column bent with a cross-beam at the top. Each column is supported on an individual foundation and a group of timber piles (300mm diameter and 10- 15-meter-deep).

21 spans (S23 to S2) Built in 1960 with a total segment length of 384 m are supported by five non-prismatic cast-in-place concrete girders. The substructure consists of two-column bents with a cross-beam at the top. Each column is supported on an individual foundation and a group of timber piles (300mm diameter and 10-15 meter deep). See **Error! Reference source not found.** for a typical retrofitted South Approach pier.

Structure 01553B – Main steel spans from Pier S2 to N2

3 spans Built in 1960 with total segment length of 205 m are supported by two hunched plate girders, steel floor beams, and concrete deck. The substructure consists of wall type bents supported on a tremie foundation seated on firm ground (till), except for bent S2 which is supported on H piles.

Structure 01553C – North Approach spans from Bent N2 to Abutment N11

9 spans Built in 1960 (CIP) and widened in 2005 (pre-cast) with total segment length of 183 m supported by four cast-in-place concrete girders and one pre-cast box girder on the east side from Bent N5 to N11. The substructure consists of two-column bents with a cross-beam at the top. Each column is supported on an individual foundation (bent N3 columns are supported on H piles).

Structure 01553D –Stewardson Way off ramp from Bent E1 to Abutment E5

4 spans Built in 1960 with total segment length of 73 m are supported by three cast-in-place concrete girders. The substructure consists of two-column bents with a cross-beam at the top. Each column is supported on an individual foundation (Bent E3 columns are supported on H piles).

BACKGROUND OF MODIFICATIONS

The 01553 Queensborough Bridge was constructed in 1960. All known major modifications to the Bridge are described below.

In 1984, the six cast-in-place approach spans south of Pier S23 were replaced with pre-stressed concrete I-girder spans from S27 to S23, reducing the total spans by two, modifying the alignment from straight to curved and constructing a new abutment to the south.

In 1993 and 1994, the south, north and Stewardson Way off-ramps underwent a seismic retrofit. Key upgrades included encasing the columns with steel jackets, installing seismic restrainers at expansion joints, post tensioning diaphragms at Piers S8 to S3, installing new elastomeric bearings directly above the columns, and converting finger plate deck joints in the South Approach and North Approach spans to compression seals. The Main Span also underwent seismic retrofit program as a part of the 1993 program. The works included column jacketing, cap-to-column joint strengthening, footing strengthening, bearing replacement, cable restrainer installation, and bracing and stiffener repairs at piers. In 1997, fibre wrapping was done at the top of columns on Pier S11. Ground improvement was undertaken with gravel drains targeted at areas near the Fraser River banks (Pier S8 to S3 and Pier N2). During these assessments, Golder Associates LTD. was engaged by the Ministry to carry out the geotechnical assessment. Additional discussion on the previous seismic retrofits is provided in **Section** Error! Reference source not found..

In 2005, over two phases, under the 91/91A Border Infrastructure Program, the Queensborough Bridge underwent a functional upgrade. Vehicular, pedestrian and cyclist safety were enhanced by widening the north and south bound sidewalks and by adding precast barriers at the median and on the shoulders. The shoulder-mounted parapets with bicycle railings serve to separate vehicular traffic from the sidewalk. The North Approaches were widened to improve the turning radius and to better accommodate heavy truck traffic. The deck widening was achieved by adding a new line of precast box girders on the east edge of the Bridge from Pier N5 to N11. Pedestrian bridges, 01553E and 01553W, were also added.

SEISMIC DESIGN CRITERIA

Seismic Hazard

As the ground at the South Approach Span is classified as soft soil type E with potential liquefaction Type F. Main Steel Span and the North Approach Span soil is classified as site class C, two sets of seismic hazard spectra are prepared with site class C and site Class E based on the (National Building Code of Canada seismic hazard values, 2015). Additionally, a set of seismic hazard spectra is provided by Golder Associates Ltd. Considering the effect of liquefaction. These spectra are compared with the seismic spectra provide by the Golder at the time of original seismic retrofit (1995) and the seismic design spectra used in the seismic retrofit design in 1995. The below naming convention is used to make the comparison more feasible:

- NBCC- [Return period]-E: (National Building Code of Canada seismic hazard values, 2015) site used to obtain the current 1:475 AEP, 1:975 AEP and 1:2475 AEP spectrums for Site Class E
- NBCC- [Return period]-C: (National Building Code of Canada seismic hazard values, 2015) site used to obtain the current 1:475 AEP, 1:975 AEP and 1:2475 AEP spectrums for Site Class C
- Golder-475-Till: 1:475 AEP spectrum calculated for borehole 3 (under bent S2 at till level) from the mean value of records used during the studies in 1995.
- Golder-475-Pile cap: 1:475 AEP spectrum calculated for borehole 3 (under bent S2 at pile cap level) from the mean value of following records during the studies in 1995.
- Calc-475-Till: 1:475 AEP spectrum represented in the (Sandwell, 1995)
- Calc-475-Pile cap: 1:475 AEP spectrum represented in the (Sandwell, 1995)

Comparison of firm ground spectra are made separately as shown in Figure 2. And the comparison for the South Approach Span area is considered separately.

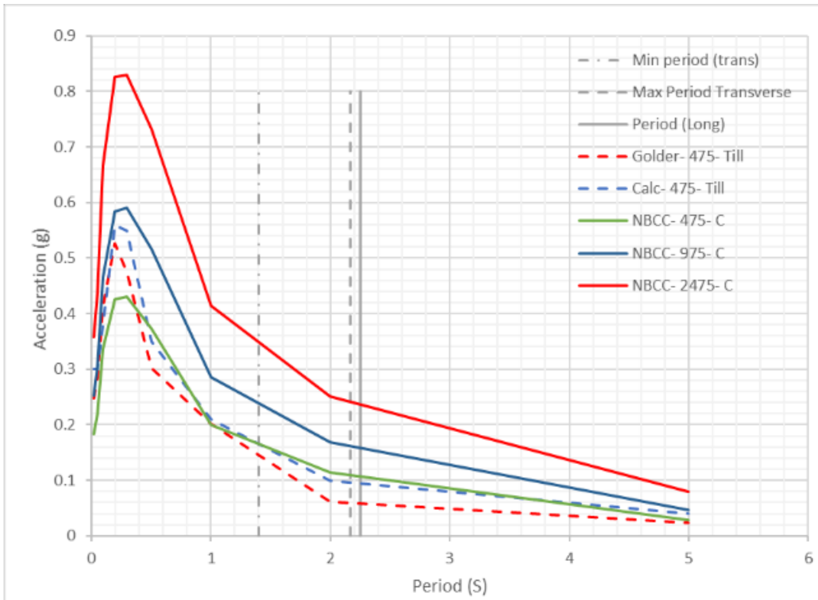

Figure 2: Comparison of firm ground seismic design spectra

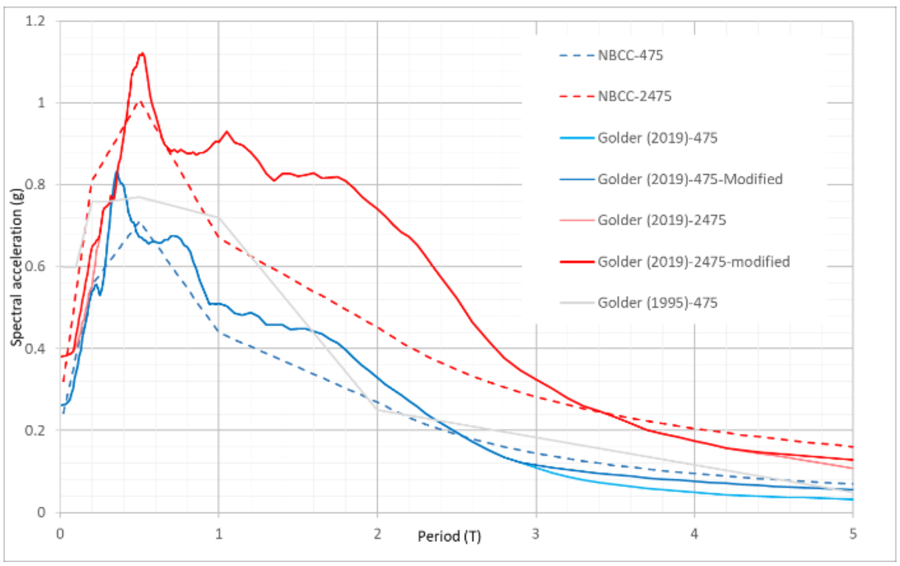

Figure 3: Comparison of (Calc-475-Surface) with (NBCC- [Return Period]-E)

Seismic Performance objectives

The 01553 Queensborough Bridge is designated as a Lifeline Bridge by the Ministry. The performance levels required for Lifeline Bridges are presented in Table 3. However, the assessment was carried out targeting the highest level of performance that can be achieved given the geotechnical vulnerabilities and without major changes to structural configuration.

Table 1: Performance levels expected for Lifeline and Major-route bridges

Annual Exceedance Probability	Lifeline Bridges		Major-Route Bridges	
	Service	Damage	Service	Damage
1:475	Immediate	minimal	Immediate	minimal
1:975	Immediate	minimal	service limited	Repairable
1:2475	service limited	Repairable	Service Disruption	Extensive

ASSESSMENT RESULTS

The preliminary seismic assessment is limited to isolated bent RSAs and ISPAs for one Main Span bent (S1) and two South Approach bent (S4 and S21). Additionally, an ISPA was conducted for an individual bent on the North Approach (N7). The scope of this assessment is not necessarily representative of the whole structure, and variations are expected for the behavior of elements and bents that have not been assessed.

Seismic vulnerabilities for the assessed bents are discussed in the following sections.

Main Span

The S2 and N2 bents attract minimal earthquake loads attributing to the low stiffness of the rubber bearing installed during the 1993 retrofit. The transverse direction strength of the Main Span bent S1 was anticipated to be noticeably higher than the longitudinal direction due to the in-plane shear walls acting transversely. The longitudinal direction of the S1 bent shows adequate strength under the 1:2475 AEP event. The structure stays essentially elastic, except for the lead rubber bearings, whose nonlinear behavior is intended by design and was accounted for. A number of possible failure mechanisms which has been checked for the bent is listed in Figure 4 on the overall geometry of the bent numbered with the order of occurrence. It is shown that the overturning of the bent at the tremie foundation is the first mechanism and can be considered as a rocking mechanism. However, this mechanism needs to be investigated further in subsequent studies to make sure that the displacement is controlled by the adjacent spans.

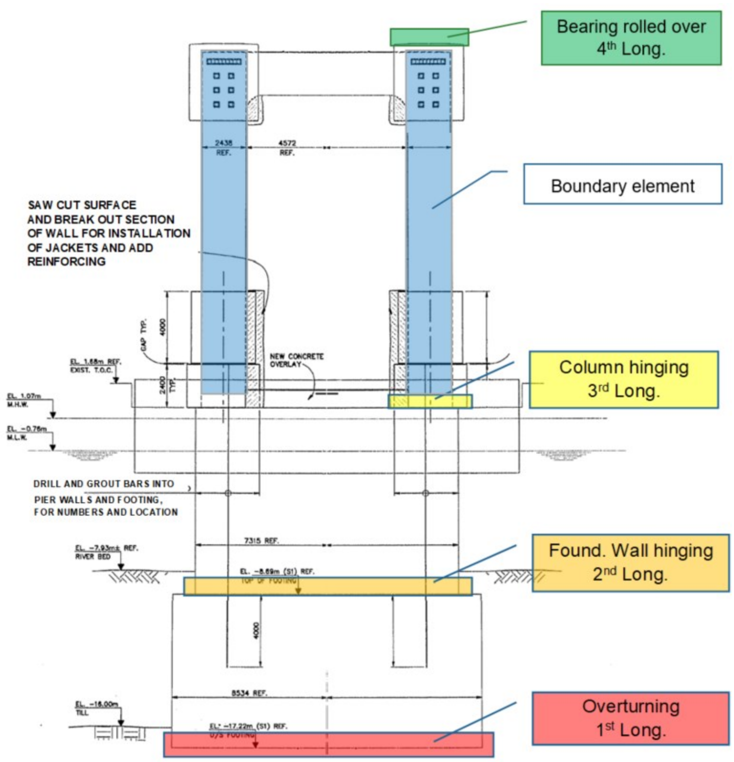

Figure 4: S1 modes of failure location

South Approach

The geotechnical assessment illustrates that the South Approach ground contains liquefiable layers that are triggered at the 1:475 AEP and the 1:2475 AEP events. The liquefaction will lead to notable ground displacement and post event settlements. Given the liquefaction potential on the South Approach ground, the performance objectives of the structure are not achievable. However, for the purpose of this section, the ground issues are set aside and the vulnerabilities discussed below are assessed based on adequate ground support for foundation. The geotechnical vulnerabilities are discussed further in Geotechnical studies section.

The existing cable restrainers do not meet the (CHBDC S6-14, 2014) requirement of Sa(0.2) multiplied by the weight of the lightest adjoining spans. Although the restrainers have a D/C of 1.36 under current code requirements, they have higher strength compared to the potential maximum demand that can be transferred to them.

The cross-beam damage level does not meet the (Supplement to CHBDC S16-14, 2016) acceptance criteria, except for the S21 under 1:475 AEP event. Increasing the cross-beam capacity will impose further demands at the top of the bent columns. Alternatively, the retrofitted superstructure diaphragms that help to transfer the structure dead load directly to the bent columns could be further strengthened to carry the full-service load of the Bridge. As the cross-beam failure should not be allowed to occur, strictly speaking, the retrofit would not meet the (Supplement to CHBDC S16-14, 2016) acceptance criteria.

Bent columns on Bents S4 and S21 meet the performance objective of Minimal Damage for the 1:475 AEP level; however, they fail to meet the performance objectives of Repairable Damage for the 1:2475 AEP event. The performance and vulnerabilities of each bent elements are laid out in in details.

It should also be noted that more precise modelling of the foundation and soil structure interaction will better estimate the overall seismic behavior of the South Approach and may improve the cross-beam and columns performance. Additionally, the spectrum used at this stage is the enveloped worst case for all bents which is conservative. Utilizing a more precise spectrum under specific bents may reduce the demands. All modes of failure for bent S4 are summarized schematically in Figure 5.

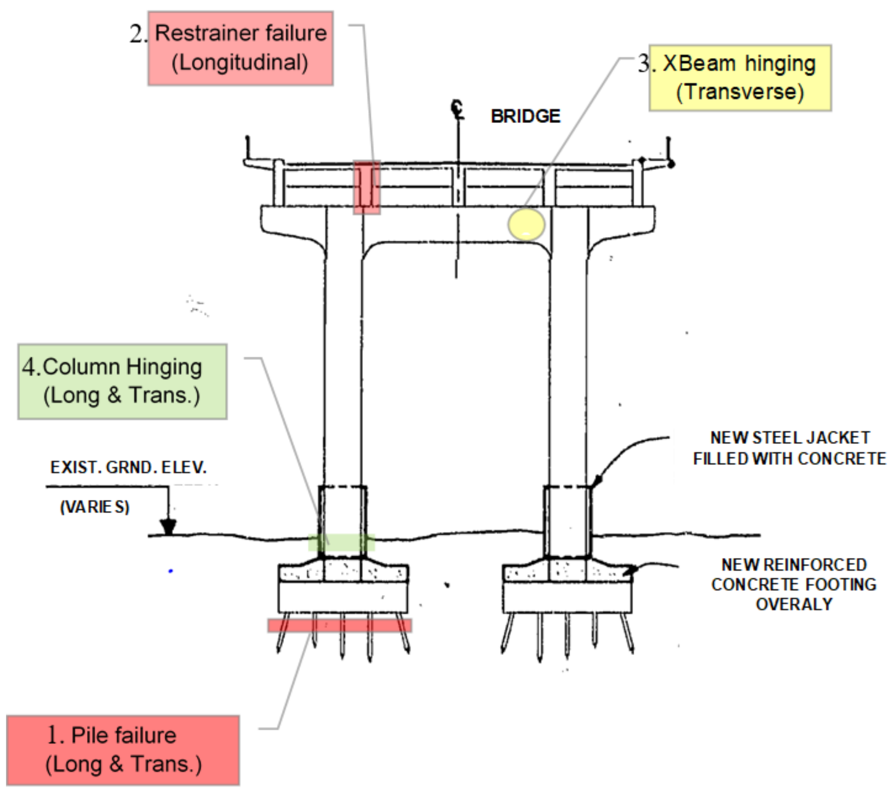

Figure 5: Three first modes of failure for S4 bent in both lateral direction

North Approach

In the longitudinal direction, all elements meet their performance criteria under both 1:475 AEP and 1:2475 AEP events. Since the N7 bent does not have any restrainers, the restrainers at N5 bent are checked against the code requirements and the code requirements are not met.

In the transverse direction, the first deficiency to manifest is the deck reaching to its moment capacity under 1:475 AEP event. The next mode of failure is found to be cross-beam shear failure under the 1:2475 AEP event. As the shear failure is a brittle mode, it needs to be addressed during the retrofit phase. If the structure performance is further assessed considering this deficiency to be fixed, the assessment shows that the rest of the elements meet the performance criteria for 1:2475 AEP.

Table 2: Performances and vulnerabilities of the Bent N7 in ideal situation

Bent and Analysis	Direction	indicator	475 situation/ Comment	475 Expected performance	2475 situation/ Comment	2475 Expected performance
Bent N7 | ISPA	Longitudinal	Restrainers	Does not meet the code requirement	May meet the Minimal Damage	Does not meet the code requirement	May meet the Repairable Damage
		Bearings	meet the criteria	Minimal Damage	meet the criteria	Repairable Damage
		Column Steel Strain	meet the criteria	Minimal Damage	meet the criteria	Repairable Damage
	Transverse	Deck steel strain	Lack of bar development length	Extensive damage	Lack of bar development length	Extensive damage
		Bearings	meet the criteria	Minimal Damage	meet the criteria	Repairable Damage
		Cross-beam Shear Capacity	meet the criteria	Minimal Damage	Slightly exceed shear capacity	possible collapse
		Column Steel Strain	meet the criteria	Minimal Damage	Added Column yielding in bending	Repairable Damage

GEOTECHNICAL STUDIES

To further understand the effects of liquefaction on the South Approach's seismic performance, Golder Associates Ltd. was engaged by the Ministry to perform a geotechnical desktop study. Results from this study are summarized below.

- Under 1:475 AEP shaking, liquefaction is predicted in the sands to a depth of about 30m. Liquefaction-induced lateral ground movements along the South Approach are expected to vary between 100 mm and 1200 mm in the north-south direction. The shear-induced vertical movements vary between -180 mm and 180 mm (negative denotes downward movement and positive denotes upward movement of heave). In addition, post-seismic reconsolidation settlements are estimated to be about 220 mm on the south side (S20 to S27) increasing to 350 mm at S15. Post-seismic reconsolidation of liquefied soils is expected to occur over a period of 1-3 days after cessation of ground shaking.
- Under 1:2475 AEP shaking, the predicted liquefaction depth and the range of lateral ground movements along the South Approach are similar to those predicted for 1:475 AEP shaking. However, the vertical movements increase to 650mm. Post-seismic consolidation settlements are estimated to be about 400 mm on the south side (S20 to S27) and increasing to 600 mm at S15.
- At S21, the computed lateral ground displacements vary from 100 to 700 mm for the 1:475 AEP shaking, whereas this range increases to 200 to 1100 mm for the 1:2475 AEP shaking.

As liquefaction was also anticipated in the (Sandwell, 1995) report, the existing retrofit concrete overlay already provides reinforcing mechanical splices for the future extension of the pile cap with additional piles. Extending the pile cap and adding new piles is one option and the ground improvement is the other option.

Regardless of the structural retrofit effort, the achievable performance objective, without ground improvement or adding piles, is limited to Life Safety at the 1:475 AEP event, and no reliable performance can be anticipated at the 1:2475 AEP event for the bridge. All of these limitations are imposed by the South Approach ground issues.

CONCLUSIONS

Main Span

At this stage it can be concluded that there is no major deficiency in the Main Span that has been identified. In the transverse direction, the Main Span bents are essentially elastic under both the 1:475 AEP and the 1:2475 AEP events. In the longitudinal direction, the bents remain elastic under the 1:475 AEP event. Under the 1:2475 AEP event, a rocking mechanism develops at the bottom of the tremie foundation. The Main Span meets the Repairable Damage performance criteria for 1:2475 AEP event within limitations of the evaluation. Lead rubber bearings added at the pervious retrofit works, improved the performance of the bent even at the higher seismic demand of the current code. This is achieved as the yielding of lead rubber bearing limits the demands transferred to the bent. The lead rubber bearings also help increase the damping of the structure which reduces the demands.

It is recommended to investigate the longitudinal performance of the Main Span in more detail during the detailed assessment of the Bridge to quantify the rocking action in the longitudinal direction. Additionally, the smaller N2 and S2 bents should be further assessed to verify their performance.

South Approach

The South Approach performance is estimated by studying a tall bent at one end (S4) and a short bent at the other end (S21). In the longitudinal direction, the performance of the structure remains consistent at the two ends of the South Approach. It can be concluded that the South Approach is at the limit of the Minimal Damage criteria under the 1:475 AEP event. The columns are at Possible Collapse Damage level under 1:2475 AEP event.

In the transverse direction, a spectrum of behavior is observed along the South Approach bents. Based on the assessment, the Bent S4 cross-beam meets the Extensive Damage criteria under the 1:475 AEP event. Though the cross-beam deficiency has not been observed in the shorter bents represented by S21, the girder lateral displacements come close to the edge of the cross-beams due to notable contribution of the bearings in total bent displacement. Therefore, it can be concluded that the likelihood of cross-beam flexural failure reduces for bents closer to the south end of the South Approach but the probability of the girder unseating increases (Section 5.2.4). The probability of exceeding the cross beams' Extensive Damage criteria under 1:2475 AEP event increases moving from the shorter bents on the south side (S21) to the taller bents (S4). Some of the columns exceed their Extensive Damage criteria. Hence, the overall South Approach performance is considered to meet Life Safety requirements under this event without considering liquefaction.

Further to the structural vulnerabilities, the ground deficiencies would lead to pile plunging and foundation rocking. The geotechnical assessment shows that the South Approach ground contains liquefiable layers that are triggered at 1:475 AEP and 1:2475 AEP events. Liquefaction will lead to notable ground displacement and post event settlements. Given the liquefaction potential on the South Approach ground, the performance objectives of the structure are not achievable with its current capacities. Extension of pile cap and adding new piles deep enough to pass the liquefiable layers are viable options to mitigate the liquefaction and rocking issues.

In addition to potential ground improvement, further structural retrofit is required to meet the performance objectives of the structure. To meet the Minimal Damage criteria under 1:475 AEP the cap beams should be post-tensioned. Although, for taller columns between S3-S8, the diaphragms are post tensioned as an alternative load path after cross-beam hinging, these diaphragms were retrofitted to life safety level and restricted service. Meeting the Lifeline bridge performance objective under 1:2475 AEP event is not possible as the columns have already been jacketed and further capacity improvement is not likely for them. However, further studies are highly recommended to consider the multi span effects. Adding dampers may also moderate the demand on the structure.

North Approach and East Ramp

The North Approach seismic performance was changed considerably by the modifications made during Border Infrastructure Program in 2005 (the functional improvement). The changes tied the North Approach to the East Ramp, specifically beyond N5, by connecting their slabs between N5 and N6 bents. It made this segment of the Bridge geometrically irregular. Girders supporting the Extended Deck is designed to be integral with the columns. This, in turn, adds asymmetrical stiffness to the span. Notable difference in seating elevation of added column foundation and original bent foundation, along with the fact that the new foundation is supported on the micro piles, adds more complexity to the North Approach performance.

The minimum required analysis to evaluate the North Approach performance under earthquake effects would be a 3D multi-modal RSA, which was out of the scope of these studies. To help evaluate the modified bent system capacity, an ISPA is carried out on an isolated bent (N7). Therefore, all the results and conclusions are limited to these assumptions and should not be extended to other bents or be used to evaluate the overall North Approach behavior.

In the transverse direction, lack of the top and bottom reinforcement in the deck leads to the first mode of failure under 1:475 AEP event. Therefore, the bent doesn't meet the performance criteria for 1:475 AEP event. Accepting deck hinging beyond the 1:475 AEP leads to shear failure of the cross-beam on the original bent under 1:2475 AEP event. As the failure is brittle, the bent won't meet the performance criteria under 1:2475 AEP.

In the longitudinal direction, all elements meet the performance criteria under both 1:475 AEP and 1:2475 AEP events. The restrainers at the N5 bent are checked against the code requirements and the code requirements are not met.

Further Considerations

Three segments of the structure have not been exclusively assessed in this study, including Spans south of Bent S23, Spans from Bents N2 to N5, and the East Ramp. Bents between S23 and S27 assumed to meet the performance objectives after the modifications on 1984. Bents N2 to N5 have similar structural capacity to the taller bents of the South Approach. Also, the demand on these bents are considerably lower due to the better firm ground condition. The performance of Bents N2 to N5 may be able to meet the code performance criteria without significant retrofit. The East Ramp bents structural capacity is in the same range as taller bents of South Approach. Although, the demand on these bents can not be estimated within the scope of these studies, the same cross-beam deficiencies are predicted.

ACKNOWLEDGMENTS

The writers wish to acknowledge the participation of Golder Associates Ltd. as geotechnical consultant for this job.

The completion of this job and this publication was not possible without the support of the BC Ministry of Transportation and Infrastructure.

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