Screening of Bridge Sites in Ontario for Liquefaction Susceptibility

Mathan V. Manmatharajan
Department of Civil Engineering, University of Toronto, Toronto, ON
David Staseff
Ministry of Transportation, Ontario, ON
Alex Sy
Klohn Crippen Berger, Vancouver, BC
Michael Snow
Golder Associates Ltd., Ottawa, ON
Mason Ghafghazi
Department of Civil Engineering, University of Toronto, Toronto, ON

ABSTRACT

Lateral ground deformation generally observed at river crossings is a pervasive type of liquefaction-induced ground failure. This can result in settlement of approach embankments, rotation and translation of abutment piles, and unseating of bridge decks. Since Ontario is situated in a generally low seismic activity region, liquefaction susceptibility and its consequences have not been comprehensively studied for its infrastructure. However, past earthquakes and seismic hazard maps of NBCC (2015) suggest that the infrastructure around the Niagara region, Ottawa region and along the Saint Lawrence River Valley can suffer earthquake-induced damage.

All Ministry of Transportation bridge sites in Ontario were screened for liquefaction susceptibility using seismic microzonation maps and the most critical ones were identified. Seismic microzonation maps were developed by combining bedrock, surficial geology, groundwater and seismic hazard data in GIS software and Google Earth. Critical bridges were identified for liquefaction potential assessment using conservatively assumed site conditions and seismic demands following AASHTO and CHBDC design codes. AASHTO recommends detailed liquefaction assessment for four bridges in eastern and central regions of the province whereas CHBDC recommends evaluation of potential for liquefaction for a much larger number of bridges. The significant discrepancy between these codes points to a need for further study. Assumptions, details of the assessment, essential pieces of information needed, and future research are discussed.

RÉSUMÉ

Aux abords des cours d’eau, la liquéfaction des sols cause fréquemment des ruptures qui se manifestent par des déformations latérales. Ceci peut engendrer le tassement de berges en remblai, la rotation et la translation des pieux d’appui et le désencrage des tabliers des ponts. L’Ontario est situé dans une région à faible activité sismique. Conséquemment, le potentiel de liquéfaction et les conséquences y étant associées n’ont pas été étudiés de manière systématique pour chacune des infrastructures. Toutefois, les tremblements de terre passés et les cartes d’aléa sismique du CNBC (2015) suggèrent que les infrastructures pourraient souffrir d’importants dommages causés par des séismes, particulièrement dans les régions de Niagara et d’Ottawa, ainsi que le long de la vallée du Saint-Laurent.

Des cartes de microzonation d’aléa sismique ont été développées en combinant des informations sur le socle rocheux, la géologie des dépôts de surface, la nappe souterraine et l’aléa sismique dans un logiciel GIS et dans Google Earth. Le potentiel de liquéfaction de tous les ponts du Ministère des Transports de l’Ontario a été examiné à l’aide de ces cartes. Les structures pour lesquelles le potentiel de liquéfaction est le plus critique ont été identifiées en adoptant des hypothèses prudentes sur les conditions du site et la contrainte sismique. En suivant les recommandations de l’AASHTO, une revue du potentiel de liquéfaction de quatre ponts dans l’est et le centre de la province serait nécessaire. Selon les recommandations du CCPCR, les analyses de potentiel de liquéfaction devraient être mises à jour pour un plus grand nombre de ponts. Les divergences entre les recommandations de ces documents de référence soulèvent des interrogations. Les hypothèses, la méthodologie, les informations clé manquantes ainsi que les études à venir sont discutées.

1 INTRODUCTION

The term liquefaction refers to the significant loss of strength and stiffness resulting from generation of excess pore water pressure in saturated soils due to seismic and sometimes static loading. Liquefaction often has damaging consequences such as flow failure, lateral spreading, excessive settlement, loss of bearing capacity, increase of active earth pressures, and loss of passive earth pressures. Lateral ground deformation, which is a pervasive type of liquefaction-induced ground failure (Youd and Bartlett, 1992), is common at river crossings where bridges are founded on alluvia. Such failures can result in cracking and settling of approach embankments, rotation and translation of abutment piles, and unseating of bridge decks.

Since Ontario is situated in a part of North America with generally low seismic activity, liquefaction susceptibility and its consequences have not been comprehensively studied for its infrastructure. However, the history of earthquakes in the past century [e.g. Cornwall–Massena, 1944; Saguenay, 1988; and Val-des-Bios, 2010] and increased ground motions required for design per National Building Code of Canada (NBCC-2015) and Canadian Highway Bridge Design Code (CHBDC-2014) suggest that the infrastructure in Ontario around the Niagara region, Ottawa region and along the Saint Lawrence River Valley can suffer earthquake-induced damage as a result of 2475-year return period (2% probability of exceedance in 50 years) design earthquakes. To accommodate seismic loading, CHBDC clause 6.7.3 requires an evaluation of active earthquake faults affecting sites, potential for surface fault rupture, site-specific ground motion parameters, site effects, liquefaction potential, and impact of liquefaction on the foundation and support structures. In addition, clause 6.17.3.1 of CHBDC indicates that integral abutments shall not be used where the soil is susceptible to liquefaction, slope instability, sloughing, boiling, or where sufficient lateral pile restraint is not provided. Integral bridge abutments are common in Ontario. Our current understanding of seismic hazard in the province, and constraints on using integral abutments make understanding of liquefaction-induced damage potential an important practical challenge for the province.

1.1 Design Code Approach to Seismic Design of Bridges

Generally, seismic design entails a comparison between seismic demand and seismic resistance. Seismic demand on a structure depends on its significance, level of seismic activity at the site, and site response. Seismic resistance of geotechnical components of a structure (e.g. foundation and embankment) is driven by types of soils and their densities among other factors. Seismic resistance is determined through site characterization using in-situ and laboratory techniques. Various design codes have approached seismic design in different ways and with various degrees of prescriptiveness. The following design codes that address seismic design of bridges were reviewed:

- AASHTO (American Association of State Highway and Transportation Officials), 2012, “AASHTO LRFD Bridge Design Specification”, 6th Edition, Washington, DC. *(referred to as AASHTO in the rest of this document)*
- CSA (Canadian Standard Association), 2014, “Canadian Highway Bridge Design Code S6-14” and commentary, Mississauga, Ontario. *(referred to as CHBDC in the rest of this paper)*
- ODOT (Oregon Department of Transportation), 2016, “Geotechnical Design Manual”, Salem, OR. *(referred to as ODOT in the rest of this paper)*
- WSDOT (Washington State Department of Transportation), 2015, “Geotechnical Design Manual M46-03-11”, Olympia, WA. *(referred to as WSDOT in the rest of this paper)*
- FHWA (Federal Highway Administration), 2014, “LRFD Seismic Analysis and Design of Bridge Reference Manual NHI-15-004”, National Highway Institute, US Department of Transportation, Washington, DC. *(referred to as FHWA in the rest of this paper)*

AASHTO specifies procedures to identify where detailed liquefaction assessment will be required. According to AASHTO (clause 3.10.6), each bridge shall be categorized as one of the four seismic zones (SZ) (between one and four) depending on the spectral acceleration coefficient, at 1.0 sec period on rock (site class B), S_{D1}. AASHTO clause 10.5.4.2 provides liquefaction design requirements in terms of site characterization for bridge sites falling under seismic zones of 3 or 4. The procedures from AASHTO are summarized as a flowchart in Figure 1.

CHBDC provides minimum requirements for seismic analysis and design of new bridges and seismic evaluation and rehabilitation of existing bridges. CHBDC clause 4.4.2 requires regulatory authorities to classify bridges into one of three major importance categories: Lifeline (LL), Major-Route (MR) or other (OT), based on social, survival, economic and security/defense requirements. Lifeline bridges are large, unique, iconic and vital for regional transportation. Major-route bridges are required to provide services for post-earthquake emergency, security and defence purposes. Bridges other than lifeline and major-route are categorized as “other”. These categories are associated with different levels of acceptable damage and required post-earthquake performance for different levels of seismic hazard.

According to CHBDC (clause 4.4.4), each bridge shall be assigned one of three seismic performance categories (SPC) (1, 2 or 3) based on the site-specific spectral acceleration, and the fundamental period of the bridge (T) for a 2475-year return period ground motion. Extra attention should be paid when using site factors from CHBDC because these factors are referenced to site class C (very dense soil & soft rock), while AASHTO references site class B (rock). CHBDC (clause 4.11.13) offers a set of criteria for when evaluation of potential for liquefaction (EPL) of foundation soils is required. The procedures from CHBDC are summarized as flowchart in Figure 2.

ODOT, WSDOT, and FHWA are extensions of the AASHTO code. WSDOT and FHWA largely follow AASHTO. However, ODOT goes beyond AASHTO for detailed liquefaction assessment. Assessments using ODOT procedure have been completed (Manmatharajan and Ghafghazi, 2018) but are not reported here for brevity. Thus, only AASHTO and CHBDC are discussed and compared in detail in this paper.

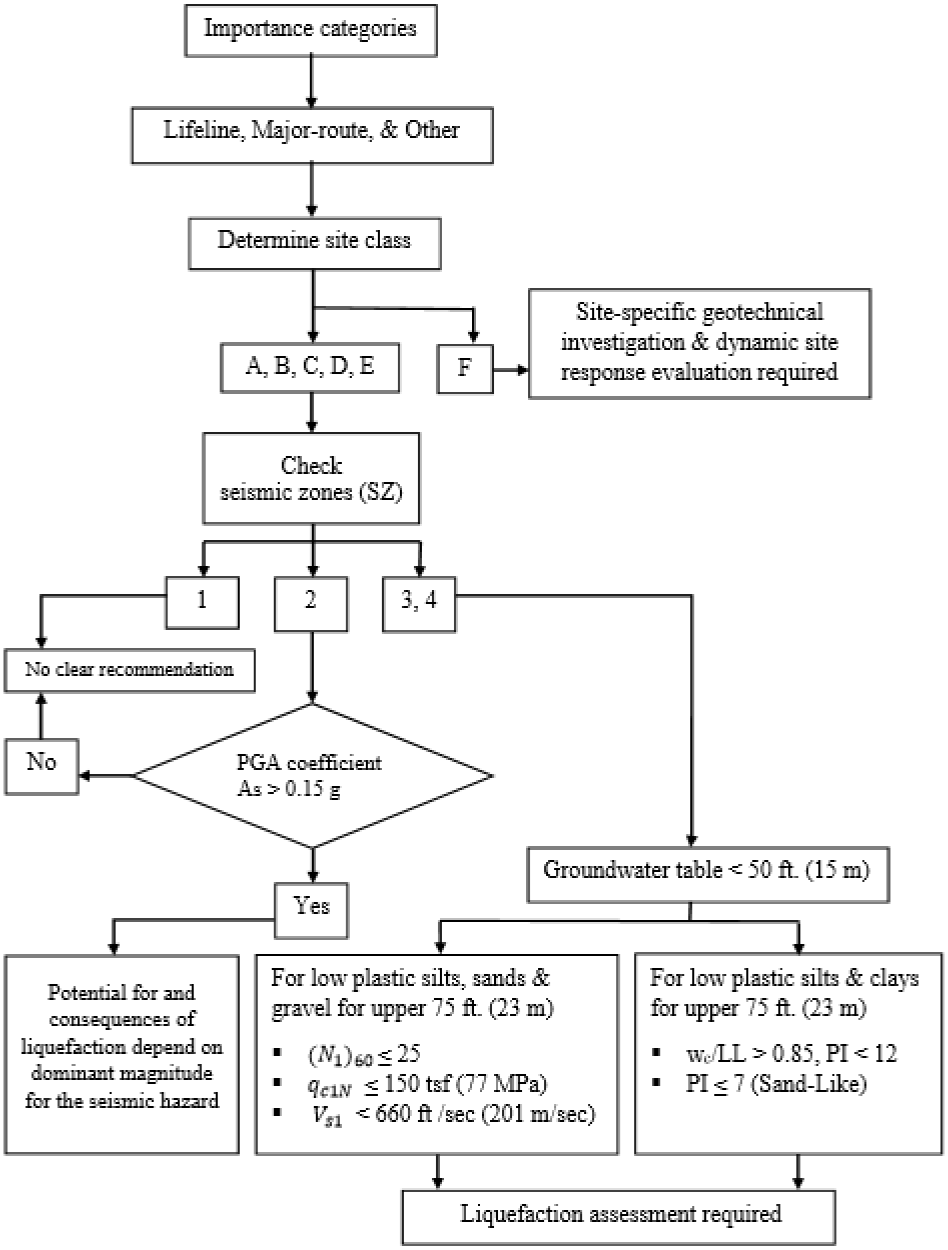

Figure 1. Flowchart explaining the screening process of seismic design of bridges using AASHTO

2 SCREENING OF MTO BRIDGES

2800 MTO bridges available in the MTO database (*https://www.ontario.ca/data/bridge-conditions*) were screened for liquefaction susceptibility and the most critical ones were identified. Microzonation maps of the entire province were developed and used to identify critical bridges.

2.1 Seismic Microzonation

A seismic microzonation map of the province of Ontario was developed. Surficial geology and topography, bedrock geology and topography, and groundwater information, as well as the 2015 seismic hazard maps were collected from different sources and combined in ArcGIS® and Google Earth®. As an example, surficial geology of southern Ontario is shown in Figure 3. For screening purposes this information is useful for identifying if there is a potential for liquefiable soils to exist in a saturated condition at a site. Moreover, the maps include seismic hazard levels which can be used to decide if further liquefaction assessment is warranted for a site where potentially liquefiable soils are present. These microzonation maps were used at various stages of the site-specific screening process described below. These maps can be used for efficiently retrieving preliminary geotechnical information for any site in Ontario and can be downloaded through www.MGLab.ca.

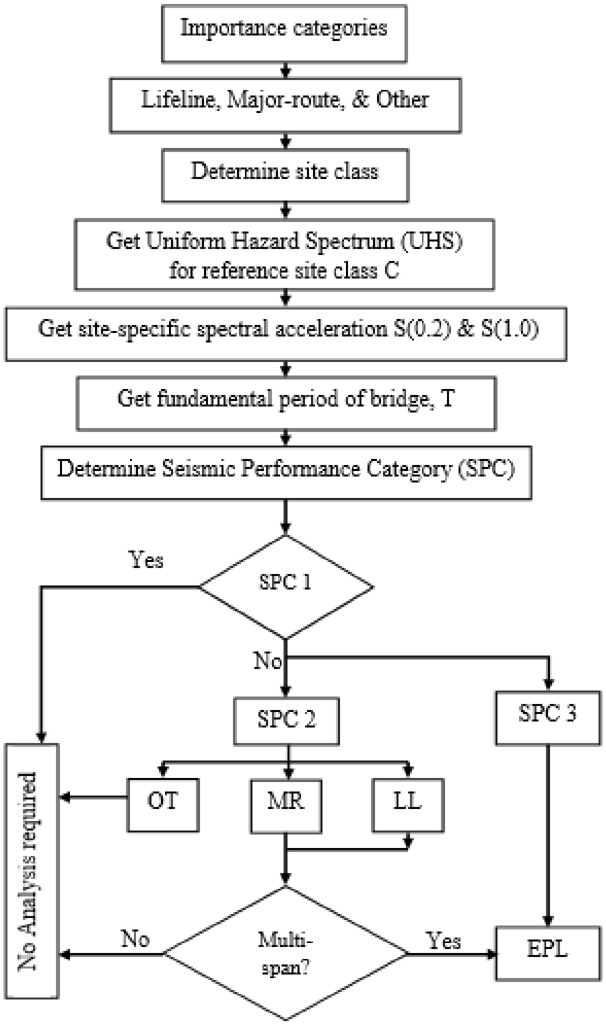

Figure 2. Flowchart explaining the screening process of seismic design of bridges using CHBDC (clause 4.11.13) *(LL- lifeline, MR- major-route, OT- other, EPL - evaluation of potential for liquefaction)*

2.2 Site Specific Screening

The site-specific screening of bridges included identifying MTO bridge sites where detailed liquefaction assessment is required by the design codes. Determining bridge importance categories and site classes are common steps between AASHTO and CHBDC design codes. The level of importance (LL, MR, and OT) was identified for all 2800 MTO bridges following a provincial engineering memorandum (Bridge Office #2016-03, July 7, 2016, Highway Standards Branch). The list was reduced to 1105 bridges (six LL, 445 MR, and 654 OT bridges) by considering a minimum design spectral acceleration of $S(0.2) = 0.2$ to identify bridges categorized as seismic performance category 2 or 3 following CHBDC, Table 4.10. This spectral acceleration ($S(0.2) = 0.2$) is associated with ground surface, while 2015 seismic hazard maps provide spectral acceleration on site class C (very dense soil and soft rock). To compute what spectral acceleration on rock corresponds to 0.2s on ground surface, site class information is needed.

Apart from the Ottawa region where $\overline{V_s}$ values have been mapped (Motazedian et al. 2011), no comprehensive database of site class is available in Ontario. So, to conservatively reduce the number of bridges to analyse, site class E was assumed everywhere and equivalent ground surface spectral acceleration $Sa(0.2) > 0.096\ g$ was computed. $Sa(0.2) = 0.96$ was determined using the minimum design spectral acceleration of $S(0.2) = 0.2$ divided by site factor, Fa of 2.08 for site class E. The site class assumption will be revisited after subsequent steps further reduce the number of sites to more manageable numbers.

Different steps are recommended by the two design codes, AASHTO and CHBDC, from this point forward as summarized in Figures 1 and 2 and discussed in the following subsections.

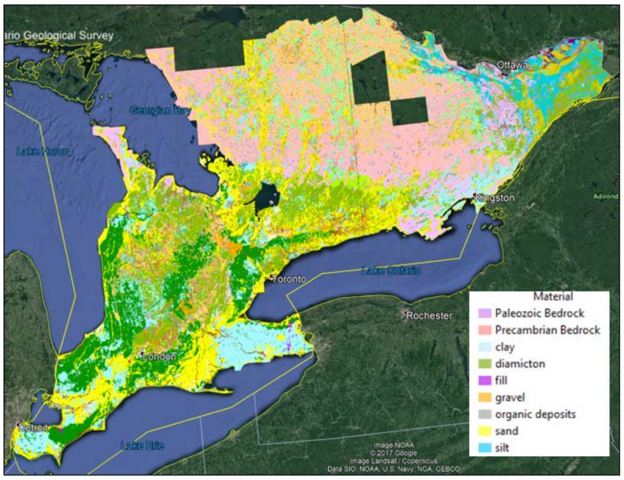

Figure 3. Surficial geology (Southern Ontario) (https://www.mndm.gov.on.ca/en/mines-and-minerals/applications/ogsearth)

2.2.1 AASHTO

AASHTO identifies 12 critical bridges including six major-route bridges categorized in SZ 3 and six lifeline bridges as shown in Table 1 following Figure 1. Locations of lifeline and major-route bridges are shown in Figures 4 and 5, respectively. Geotechnical reports completed at or near the critical bridge sites were obtained from the MTO database (http://www.mto.gov.on.ca/FoundationLibrary/map.shtml?accepted=true). Following a review of relevant information including soil profiles, SPT blow counts (N), undrained shear strengths (s_u), plasticity indices, water contents, and consistency or compactness gathered from these reports.

Using this information, the site class assumption was re-evaluated for each critical bridge site. At all MR bridge sites, a dense stratum was encountered at a maximum depth of 15 m. The dense stratum is a term used for coarse sand and gravel-limestone boulder-till or limestone bedrock. Because of shallow depth to dense stratum, firm to very stiff or compact to dense soil layer within this shallow depth and boulder till or bedrock in the dense stratum, site class C was assigned to the six MR bridge sites, as shown in Table 2.

The six LL bridges except Long Sault bridge were assigned site class D since the blow counts per 0.3 m in the upper 30 m were observed to be between 15 and 30. In the vicinity of Long Sault site, dense to very dense glacial till was encountered at shallow depth. Therefore, this bridge site was assigned site class C as shown in Table 2. The evaluation process was repeated following the newly assigned site classes. AASHTO does not require performing a detailed liquefaction assessment on the MR bridges except Wood Creek bridge and the LL bridges except Garden City Skyway, Norrish Whitney, and Burlington Skyway bridges as shown in Table 2.

Figure 4. Locations of the lifeline bridges identified by AASHTO

Figure 5. Locations of the major-route bridges identified by AASHTO

2.2.2 CHBDC

CHBDC provides minimum requirements for seismic analysis and design of new bridges and seismic evaluation and rehabilitation of existing bridges. The fundamental period of all bridges (T) was assumed to be less than 0.5 s following discussion with MTO.

A total of 979 bridges (six LL + 413 MR + 560 OT bridges) were categorized as SPC 3 and the rest (126 bridges; 32 MR + 94 OT bridges) were categorized as SPC 2.

Requirements for evaluation of potential for liquefaction (EPL) of foundation soils for existing bridges are provided in CHBDC, clause 4.11.13 as summarized in Figure 2. Following the CHBDC, clause 4.11.13, a total of 979 bridges (six LL + 413 MR (273 multi-span + 140 single span) + 560 OT bridges (423 multi-span + 137 single span)) were categorized as SPC 3 and require evaluation of potential for liquefaction. 13 major-route bridges categorized as SPC 2 and multi-span require evaluation of potential for liquefaction.

A total of 992 bridges require evaluation of potential for liquefaction following CHBDC. Retrieving the geotechnical information for this number of sites was beyond the scope of this manuscript. For demonstration, the critical lifeline (six) and major-route (six) bridges summarized in Table 1 following AASHTO were reassessed using CHBDC clause 4.11.13 with newly assigned site classes given in Table 2 and SPC given in Table 3. Following the newly assigned site classes shown in Table 2, SPC was re-assigned to the twelve bridges as shown in Table 3.

Table 1. Identified critical bridges following AASHTO with an assumption of site class E

Bridge type	Structure	MTO region	Hwy name	S_{D1}	SZ
Major-route	Cornwall Centre	ER[1]	401	0.300	3
	CNR Overhead	ER	401	0.302	3
	Raisin River	ER	401	0.308	3
	Westly Creek	ER	401	0.309	3
	Sutherland Creek	ER	401	0.309	3
	Wood Creek	ER	401	0.309	3
Lifeline	Garden City Skyway	CR[2]	QEW	0.151	2
	Long Sault	ER	34	0.271	2
	Norris Whitney	ER	62	0.128	1
	Burlington Skyway	CR	QEW	0.130	1
	Hogg's Hollow Collector	CR	401	0.117	1
	Leslie St/CNR Overhead	CR	401	0.119	1

[1]-ER = Eastern Region, [2]-CR = Central Region

Table 2. Bridges identified by AASHTO using site class E with newly assigned site class and need of liquefaction assessment

Bridge type	Structure	Site class	Liquefaction assessment required?
Major-route	Cornwall Centre	C	No
	CNR Overhead	C	No
	Raisin River	C	No
	Westly Creek	C	No
	Sutherland Creek	C	No
	Wood Creek	C	Maybe[1]
Lifeline	Garden City Skyway	D	Maybe
	Long Sault	C	No
	Norris Whitney	D	Maybe
	Burlington Skyway	D	Maybe
	Hogg's Hollow Collector	D	No
	Leslie St/CNR Overhead	D	No

[1]-Maybe- MTO may request to perform.

Table 3. Following CHBDC, SPC assigned to major-route and lifeline bridges identified by AASHTO

Bridge type	Structure	S (0.2)	SPC
Major-route	Cornwall Centre	0.588	3
	CNR Overhead	0.589	3
	Raisin River	0.589	3
	Westly Creek	0.598	3
	Sutherland Creek	0.598	3
	Wood Creek	0.598	3
Lifeline	Garden City Skyway	0.410	3
	Long Sault	0.504	3
	Norris Whitney	0.218	3
	Burlington Skyway	0.350	3
	Hogg's Hollow Collector	0.204	3
	Leslie St/CNR Overhead	0.207	3

Table 4. Requirement Evaluation of Potential for Liquefaction (EPL) (CHBDC, clause 4.11.13) for major-route and lifeline bridges identified by AASHTO.

Bridge type	Structure	Span	EPL required?
Major-route	Cornwall Centre	Single	Yes
	CNR Overhead	Multi	Yes
	Raisin River	Multi	Yes
	Westly Creek	Single	Yes
	Sutherland Creek	Multi	Yes
	Wood Creek	Single	Yes
Lifeline	Garden City Skyway	Multi	Yes
	Long Sault	Multi	Yes
	Norris Whitney	Multi	Yes
	Burlington Skyway	Multi	Yes
	Hogg's Hollow Collector	Multi	Yes
	Leslie St/CNR Overhead	Multi	Yes

Following Table 2, 3, and CHBDC, clause 4.11.13, all of the twelve LL and MR bridges require evaluation of potential for liquefaction of foundation soils as shown in Table 4.

3 DISCUSSION

AASHTO gets into prescriptive screening procedures for identifying when a more detailed liquefaction assessment is required. All these codes use crude versions of the simplified case-history-based method (e.g. Boulanger and Idriss, 2014) to evaluate whether liquefaction assessment will be required, using input parameters that are similar, or identical to those used by the simplified method (e.g. PGA and $(N_1)_{60}$). Instead of using these crude procedures, it is recommended that the simplified method itself be used given that this will likely require limited amounts of additional work or information.

The reviewed codes ignore the potential of cohesive soils (e.g. Leda clay) to cause earthquake-induced damage in bridge components. Liquefaction is by definition a phenomenon pertaining to cohesionless soils. This does not mean that cohesive soils such as clays or intermediate soils (e.g. silts and low plasticity clays) do not undergo large deformations induced by earthquake loading. There are just different sets of procedures heavily relying on undisturbed sampling and advanced laboratory testing for assessing the potential damage induced by such soils. AASHTO and CHBDC recommend liquefaction assessment for intermediate soils but are silent about cohesive soils.

4 CONCLUSION

2800 MTO bridges were screened for potential susceptibility to liquefaction through development of a microzonation map.

Microzonation maps, which include surficial topography and geology, bedrock topography and geology, seismic hazard maps, and groundwater information, were developed and integrated within Google Earth® and ArcGIS®.

Microzonation maps were used to quickly retrieve the information needed to identify critical bridge sites where liquefaction potential assessment is required by AASHTO or CHBDC design code.

AASHTO requires performing liquefaction assessment on one major-route and three lifeline bridges.

CHBDC with an assumption of site class E requires evaluation of potential for liquefaction on six lifeline, 426 major-route, and 560 other bridges. However, these bridges should be reassessed by reassigning site class after retrieving detailed geotechnical information. A reassessment of 12 of these sites, performed for demonstration, does not suggest any reduction in the number of sites. The significant discrepancy between these codes points to a need for further study.

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