Technical Review Board
Memorandum

Date: January 27, 2020

Issue: **Liquefaction Guidelines for Inland Richmond Schools**

Discussion:

Over the past two years, the Technical Review Board Steering Committee (TRBSC) has been working with leading geotechnical experts in British Columbia to develop liquefaction guidelines that better estimate liquefaction-induced soil movements following the design-level seismic event. The primary focus of this work has been in Richmond as there are a large number of seismic upgrades required for Richmond School District (SD38) schools. It is important to understand the level of liquefaction related upgrades required for these schools and to provide SD38 and the Ministry of Education (EDUC) with the best information possible.

The project lead for this work on behalf of the TRBSC, and EDUC, is John Sherstobitoff of Ausenco. Geotechnical expertise was primarily provided by Paul Wilson (Thurber Engineering Ltd.), with ongoing review by Upul Atukorala (Golder Associated Ltd.) and early involvement W.D. Liam Finn (PEACS Ltd.) and Kai-Sing Hui (exp.).

Please see the attached four-page document "Evaluation of Liquefaction-Induced Displacements for Inland Richmond Schools" submitted by Paul Wilson and Upul Atukorala. Please also note these guidelines will be expanded to cover other areas within British Columbia over the next eight months, and will be a part of the updated Seismic Retrofit Guidelines that will be released in the fall of 2020.

If you have any questions regarding the contents of this memorandum, please contact the TRB Manager, Phillip Chambers, or John Sherstobitoff. Contact information is as follows:

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- John Sherstobitoff, (604) 638-4512, john.sherstobitoff@ausenco.com

Date: December 6, 2019

Issue: Evaluation of Liquefaction-Induced Displacements for Inland Richmond Schools

From: Golder Associates Ltd. / Thurber Engineering Ltd.

Engineers and Geoscientists BC, through coordination with the Technical Review Board (TRB), retained Thurber Engineering Ltd. to develop a framework for evaluating liquefaction-induced displacement for Richmond schools that are setback more than 300 m from the Fraser River and have a non-liquefiable crust thickness greater than 3 m. EXP Services Ltd., Golder Associates Ltd. and W.D. Liam Finn (PEACS Ltd.) were retained by EGBC to review the draft evaluation framework proposed by Thurber for inland Richmond schools. Golder and Thurber were retained to finalize the evaluation framework.

The proposed evaluation framework includes geotechnical analysis methods beyond those prescribed in Part A, Volume 11 of the Seismic Retrofit Guidelines, 3rd Edition. The applicability of the framework was assessed using detailed analysis by Thurber and EXP from Ferris Elementary and a screening level study on the majority of Richmond schools.

The consensus evaluation steps for estimation of liquefaction-induced soil movements at the foundation level, as defined in Part A, Section 4.3, Volume No. 11, Liquefaction Guidelines, of the Seismic Retrofit Guidelines 3rd Edition, are:

1) Site Characterization
    a) Obtain 4 pulse per square meter or higher resolution LiDAR survey within and 100 m beyond the school property
    b) Characterize non-liquefiable crust thickness and strength at and around the school
        i) Holes around school structure perimeter at 50 m spacing; minimum four (4)

        ii) Holes away from the school structure at the base of larger slopes /ditches identified from the LiDAR; as required

        iii) Methods
            (1) CPT to 9 m; minimum two (2) CPTs to 30 m; minimum one (1) CPT to 30 m with downhole seismic measurements
            (2) Solid stem augers at half of CPT locations
                (a) Nilcon Vane shear strength measurements at two depths in silt layers at half of augers
                (b) Grab samples for in-situ moisture content and Atterberg Limits at maximum intervals 1.5 m

        iv) Anticipated scope
            (1) Approximately one-day investigation for elementary schools
            (2) Approximately two-day investigation for high schools

    c) Obtain underside of footing elevations (expose and survey if necessary) to determine 'net' crust thickness beneath footings

    d) Define unfactored net footing loads per Section 4.2 (3rd bullet) of Liquefaction Guidelines

e) Use historical school drawings to locate and measure pile dimensions, spacing and gap below pile cap, if present. If refinement of ΔV estimate in line (7)(d)(i) below is required, expose several pile caps to measure gap between pile caps and grade.

2) Seismic Hazard
   a) Use PGA=0.3g for peak ground surface acceleration in liquefaction triggering in 4a
   b) Use M=7 for magnitude in liquefaction triggering in 4a
   c) Select Site Class (D or E) for structural evaluation based on shear wave velocity measurements

3) Resistance under Inertial Loading
   a) Estimate unfactored ultimate bearing resistance using soil parameters determined from site investigation. Apply a geotechnical resistance factor of 1.0 to determine the factored bearing resistance under seismic inertial loading prior to the onset of liquefaction.

4) Liquefaction Susceptibility and Post-Cyclic Strength
   a) Identify soil layers that are liquefiable or susceptible to cyclic strength reduction per Section 2.0 of Liquefaction Guidelines using Idriss and Boulanger (2014);
   b) Estimate post-cyclic strength for soil layers using Figure 90 in Idriss and Boulanger (2008), lower curve for 'conditions where void redistribution effects could be significant'.
   c) Divide the school site into four (4) equal quadrants (see example in Figure A.2) and take the lowest crust thickness and post-cyclic strength from all the CPTs/augers in a given quadrant.

5) Lateral Displacements
   a) Complete limit equilibrium analysis for each quadrant to estimate yield acceleration (ky) checking circular and non-circular slip surfaces, taking the lower factor of safety from the circular and non-circular searches (an example will be provided in the updated Liquefaction Guidelines). Selection of the non-liquefiable crust strength and thickness for the analysis should be reasonably conservative to account for potential heterogeneity of crust.
   b) Estimate median horizontal displacement (D) using Equation 6 in Bray and Travasarou (2007) with ε=0, PGA=0.3g and M=7.

$$
\begin{aligned}
\ln(D) = & -0.22 - 2.83\ln(k_y) - 0.333(\ln(k_y))^2 \\
& + 0.566\ln(k_y)\ln(\mathrm{PGA}) + 3.04\ln(\mathrm{PGA}) \\
& - 0.244(\ln(\mathrm{PGA}))^2 + 0.278(M-7) \pm \varepsilon
\end{aligned}
$$

   c) Estimate differential horizontal displacement using the Youd et al. (2002) method detailed in Appendix A with a 4H cut-off. Per the Seismic Retrofit Guidelines, 3rd Edition, use a mean site acceleration of 0.2g and M=7 for the calculation. Use engineering judgment when applying the method for geometries with short slope lengths (i.e. less than 10 m) and small slope heights (i.e. less than 0.5 m). Selection of the non-liquefiable crust thickness for the analysis should be reasonably conservative to account for potential heterogeneity of crust.
   d) Take the greater of the mean horizontal displacement calculated in (b) and the differential horizontal displacement in (c) as the ***differential horizontal movement*** between footings. Develop a ***differential horizontal movement*** plan for structural evaluation (see example in Figure A.3). For closely spaced footings (<4 m), use engineering judgment to estimate a lesser differential horizontal displacement.
   e) If ***differential horizontal movement*** in (d) above results in the requirement for major structural foundation modifications, discuss with TRB geotechnical representative if completing a non-

linear time history analysis using FLAC, Plaxis or similar to refine displacement estimates would be of value.

6) Vertical Displacements
   a) Due to Punching Shear
      i) Based on crust characterization, geotechnical engineer to provide factored punching shear resistance per lineal m of footing perimeter; ignoring bearing resistance provided by liquefiable layer; using resistance factor of 1.0.
      ii) The potential for elements such as landscape berms or raised playground platforms to induce punching shear of the adjacent school building to be evaluated if the berm is offset less than 10 m from the school and is more than 0.5 m high.
      iii) The potential for punching to be assessed by comparing factored punching shear resistance to unfactored net footing loads. If the potential for punching shear exists, structurally connected foundations or relocating the berm, platform or element of concern is required.
   b) Due to Consolidation after Liquefaction
      i) Estimate post-liquefaction total vertical settlement using Ishihara & Yoshimine (1992) per Section 3.7 of the Guidelines, then apply Cetin et al (2009) depth weighting factor
      ii) Estimate *differential vertical movement* as 50% of the total vertical settlement. If the net crust thickness below footings is greater than or equal to 2 m, use an inclination of 60H:1V when applying *the differential vertical movement* to account for crust attenuation. If the net crust thickness below footings is less than 2 m, assume no crust attenuation.

7) Assessment of Piles
   a) Assume piles do not contribute to axial or lateral support for inertial loading, when pile embedment into cap is equal to or less than 150 mm. For compression resistance under inertial loads, assume that the pile cap and grade beams are bearing on soil.
   b) Assume piles do not contribute to axial or lateral support for post-seismic loading.
   c) Assume piles do not contribute to punching shear resistance. Ignore piles and evaluate susceptibility of pile cap and grade beams to punching shear.
   d) Vertical displacements due to closure of gap below pile caps
   i) Unless otherwise verified by field measurements, assume a gap thickness of 50 mm. Add the gap thickness to the *differential vertical movement* estimate.

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Jan 29

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Appendix A – Calculating differential horizontal movements using Youd et al. (2002) with a 4H depth cut-off

For each quadrant, define effective slopes for the near and far side of school as:

$$W_1 = \frac{H_S}{L_{S1}} \times 100\% \qquad W_2 = \frac{H_S}{L_{S2}} \times 100\%$$

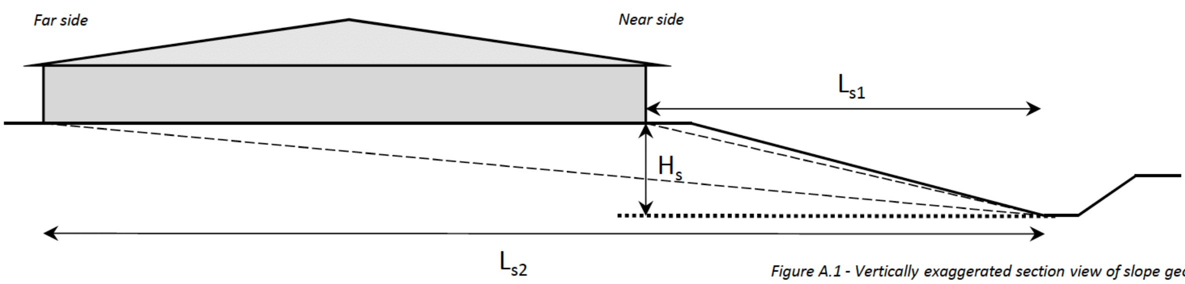
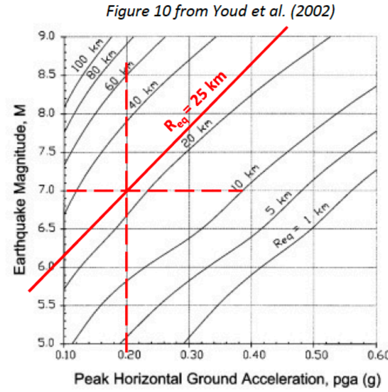


Figure A.1 - Vertically exaggerated section view of slope geometry

Estimate horizontal deformations, D_H, for far and near sides using equation 6a from Youd et al. (2002) for free-face conditions:

$$\log D_H = -16.713 + 1.532M - 1.406 \log R^* - 0.012R$$
$$+ 0.592 \log W + 0.540 \log T_{15} + 3.413 \log(100 - F_{15})$$
$$- 0.795 \log(D50_{15} + 0.1 \ \text{mm}) \qquad (6a)$$

Figure 10 from Youd et al. (2002)



$$\textit{where:} \quad T_{15} = 4 \times H_S - \textit{Crust Thickness} \geq 0.1\ m$$
$$F_{15} = 5\%$$
$$M = 7$$
$$D50_{15} = 0.29\ mm$$
$$a_{avg} = 0.2\ g\ (\textit{use as PGA in Figure } 10)$$
$$R = R_{eq} = 25\ km$$
$$R^* = R + R_0$$
$$R_0 = 10^{0.89M - 5.64}$$

Estimate differential horizontal deformations for each quadrant: $\Delta H_{Youd} = D_{H_1} - D_{H_2}$

Use engineering judgement to create a differential horizontal movement plan for structural evaluation of footings:

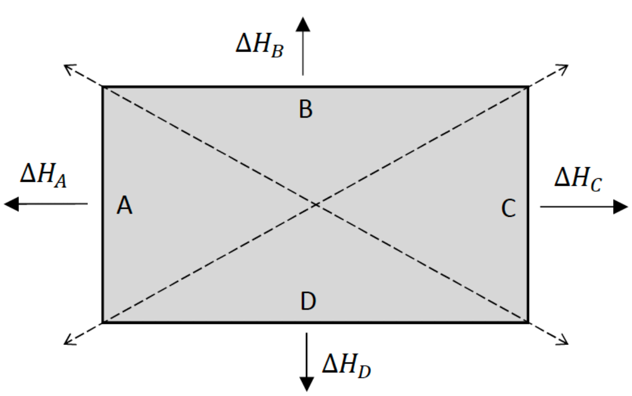


Figure A.2 - Plan view of school building divided into quadrants A, B, C, D

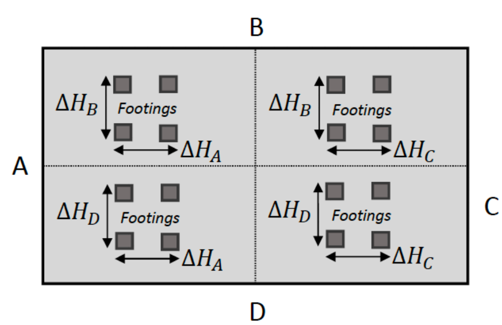


Figure A.3 – Example school horizontal movement plan