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EVALUATING LIQUEFACTION POTENTIAL AND LATERAL SPREADING FOR PROBABILISTIC GROUND MOTIONS

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ABSTRACT: Liquefaction potential and lateral spreading are evaluated in engineering practice using deterministic procedures based on a design magnitude, M, and an associated Peak Ground Acceleration, PGA. In a probabilistic ground motion environment, a wide range of magnitudes contribute to the PGA. A common solution adopted to cope with the problems this poses for the deterministic approach is to select a single magnitude somewhat close to the maximum magnitude to represent the combined effects of all the magnitudes contributing to the hazard. However there is no measure of whether this approach is appropriate. In 2007 Finn and Wightman introduced a magnitude deaggregation method for evaluating liquefaction potential and showed that current practice was overly conservative for the code ground motions. This paper evaluates the performance of current practice for the proposed NBCC2015 ground motions and extends the deaggregation method to the calculation of lateral spreading based on Youd's empirical equation (Youd et al., 2002). Some case histories of recent applications in school retrofit projects of the conventional approach and the deaggregation method are presented to highlight the difference in results.

1. Introduction

The generally accepted state of practice since 2001 for assessing the potential for triggering liquefaction has been Youd et al. (2001). EERI published a monograph by Idriss and Boulanger in 2008 entitled "Soil Liquefaction during Earthquakes" which conducted a global review of research and practice up to 2007 and made new recommendations for evaluating the triggering of liquefaction. The monograph has now assumed the status of state of practice in British Columbia (BC) and has been adopted as the basis for this study.

The evaluation of liquefaction potential involves comparing the seismic demand posed by the earthquake shaking to the capacity of the site to resist liquefaction. The capacity is usually expressed in terms of penetration resistance measured by either the Standard Penetration Test (SPT) or the Cone Penetration Test (CPT) or by shear wave velocity (V_s). The demand is given by the average Cyclic Stress Ratio, CSR, evaluated by the simplified method given below.

1.1. Simplified method for seismic stress analysis

The simplified approach estimates average cyclic stress ratio caused by earthquake shaking using Equation 1,

$$CSR = 0.65 \frac{a_{\max}}{g} \frac{\sigma_{v0}}{\sigma'_{v0}} \frac{r_d}{MSF} \tag{1}$$

where a_{max} = peak ground surface acceleration, g = acceleration of gravity (in same units as a_{max}), σ_{vo} and σ'_{vo} = total and effective vertical stresses at the depth of interest, and r_d = depth reduction factor, and MSF is a Magnitude Scaling Factor which weights the contribution of each magnitude to liquefaction potential relative to the reference magnitude M7.5. For M7.5, MSF=1.0. The MSF according to Youd et al. (2001), Idriss and Boulanger (2008) and a proposed update in Boulanger and Idriss (2014) are given in Figure 1. It is clear that there has been a continuing significant reduction in MSF values over the last 15 years. Other things being equal, the Boulanger and Idriss (2014) MSF will lead to much larger CSRs for smaller earthquake magnitudes below M6.5.

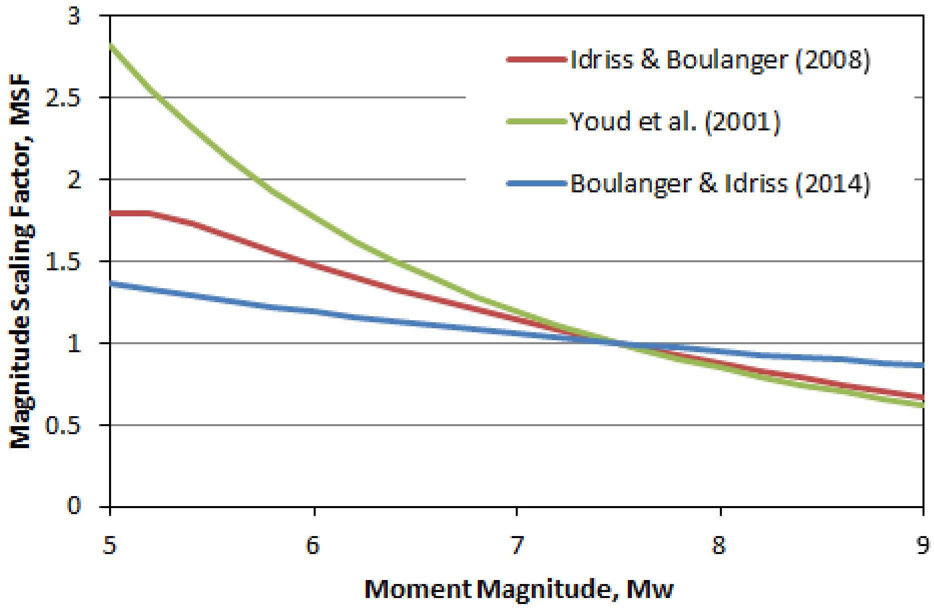

Fig. 1 – Comparison of Youd et al. (2001), Idriss and Boulanger (2008) and Boulanger and Idriss (2014) Magnitude Scaling Factors

1.2. Rigorous stress analysis

A more rigorous approach to computing the seismic shear stresses due to an earthquake is to use site response analysis. The analysis should be performed with a suite of input motions scaled over an appropriate period range to the Uniform Hazard Spectrum (UHS) for the site with an exceedance rate of 2% in 50 years. The number of input motions required depends on the number of different types of earthquake sources. The BC seismicity is driven by three types of sources; crustal, subcrustal and subduction. In conducting sites response analyses in support of the BC school seismic retrofit program, 20 motions per source type are used. There is no consistent practice in how these multiple responses are processed to provide the average cyclic stress ratio required by the liquefaction assessment charts based on SPT-N, CPT q_c and V_s data.

The site response analyses provide time histories of shear stresses, not the average shear stresses required by the liquefaction assessment charts. Approximate methods are used to determine the average shear stress introducing unknown uncertainties in the evaluation of the average shear stress. It is also important to note that the liquefaction assessment charts are based on the stresses computed by the simplified method. Is the peak ground acceleration, PGA, more appropriate when determined by site response analysis? PGA is a very unstable parameter and is highly dependent on the selected ground motions and how they are scaled to the uniform hazard spectrum, by linear or spectral matching. With regard to this, it is interesting to note that Boulanger et al. (2013) formulated the procedure for assessing liquefaction potential as follows: “the formal assessment of liquefaction at a site using the simplified procedure should be based on the a_{max} that is estimated to develop in the absence of soil softening or liquefaction”.

1.3. SPT-based resistance

In this paper, due to space limitations, only SPT-based liquefaction evaluation procedures are considered. The liquefaction assessment chart is based on the correlation of liquefaction resistance to the corrected Standard Penetration Resistance of the soil, $(N1)_{60cs}$. The correction process involves the application of a number of correction factors to the field measured SPT resistance. The necessary corrections are described in Idriss and Boulanger (2008).

The liquefaction resistance of the site is defined by the Cyclic Resistance Ratio (CRR), which is the value of CSR when the FS is one. The correlation of CRR for σ’=1atm and magnitude M7.5 with normalized and corrected SPT values, $(N_1)_{60cs}$, is shown in Figure 2. Note that the bounding curve for M7.5, the reference magnitude, given by Youd et al. (2001) and Idriss and Boulanger (2008) are very similar. However for M6.0, the different approaches to scaling factors result in significantly different CRR correlations with $(N_1)_{60cs}$ as shown in Figure 2 also. The impact of the different scaling factors will be noticeable primarily for sources with M_{max}≤6.5.

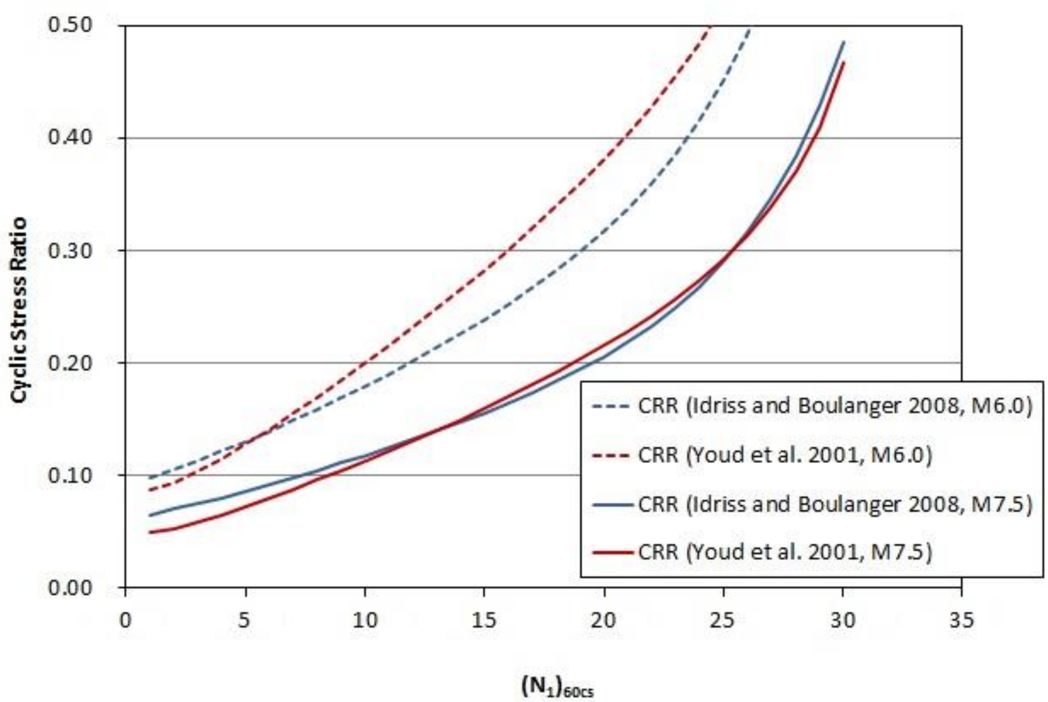

Fig. 2 – Liquefaction resistance curves for M6.0 and M7.5 using the Youd et al. (2001) and Idriss and Boulanger (2008) procedures

1.4. Simplified method using probabilistic accelerations

The simplified method described above is deterministic. The seismic hazard at the site is based on a known pair of parameters, M and a_{max}. Therefore, the MSF for M can be applied directly in Equation 1. However, if a probabilistic PGA is used, which is the result of the contributions of many magnitudes to PGA, what magnitude and hence what MSF should be used? In current practice a single magnitude is often selected which tends towards the maximum or mode magnitude expected and its weighting factor is used with the NBCC2015 PGA. In Vancouver prior to 2007 M7.3 was recommended for use. In 2007 M7.0 was suggested. Do these suggested magnitudes represent adequately the combined effects of the many different magnitudes contributing to the probabilistic PGA? The answer to this question is not a matter of opinion but can be demonstrated directly by two independent methods: (1) a probabilistic seismic hazard analysis using weighted magnitudes and (2) a procedure based on a magnitude - distance deaggregation for the BC code hazard level of a 2% exceedance rate in 50 years. The weighted magnitude probabilistic analysis approach has been described in Finn and Wightman (2007). It is not presented here because it requires access to a seismic hazard analysis program that must be leased. The deaggregation method is easy to implement because the magnitude-distance deaggregation is available from GSC. Finn and Wightman (2007) have shown that both the weighted magnitude and deaggregation methods give the same results.

1.5. Magnitude deaggregation method

Simply put, magnitude deaggregation (Figure 3) gives a set of magnitudes and their per cent contributions to the site acceleration. The FS of the site is computed for each binned magnitude in the deaggregation using the simplified method modified by the appropriate scaling factor for each magnitude. Individual factors of safety are multiplied by the per cent contribution of that magnitude to the site acceleration. The sum of all the contributions to the factor of safety gives the global factor of safety for the site.

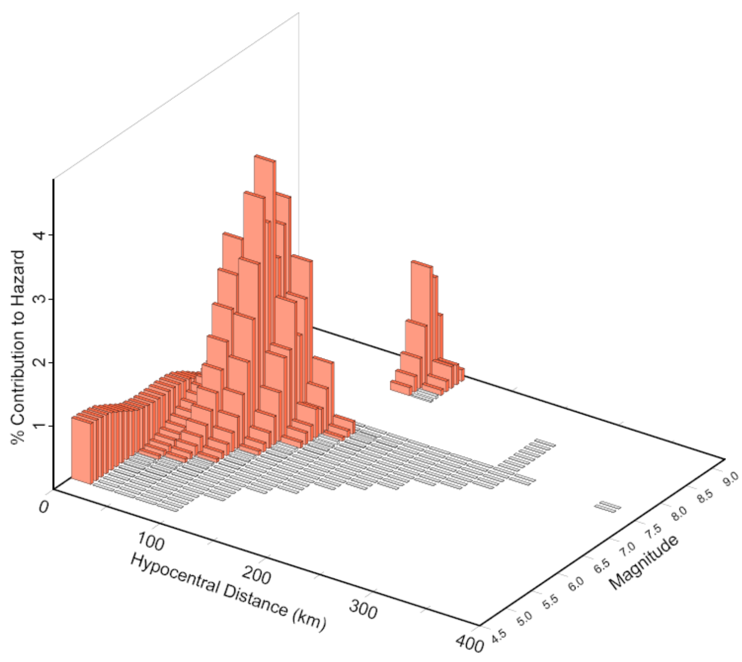

Fig. 3 – Magnitude-distance deaggregation for NBCC2015 PGA in Vancouver

The Factor of Safety (FS) against liquefaction triggering is calculated for a range of site conditions in Vancouver. The probabilistic PGA with an exceedance rate of 2% in 50 years is given by NBCC2015 as PGA=0.367g. The site conditions were assumed to be clean sand, with a total unit weight 20 kN/m^3 below the water table, a unit weight of 17.2 kN/m^3 above the water table, a water table at 2m depth, and a range of $(N_1)_{60}$ values (10-30) at 6 m depth. The Idriss and Boulanger (2008) magnitude scaling factors are used. The factors of safety from the deaggregation method are shown in Table 1. The factors from current practice in the Lower Mainland of using M7.0 with PGA and those arising from using mean magnitude, M6.93, are also shown. For practical purposes, the three methods give similar results. Under the previous code NBCC (2010), use of M7.0 significantly underestimated the FS value. In that case the mean magnitude which gives the correct FS was M6.3, which makes it clear why M7.0 was underestimating the FS value. Under NBCC2015, the average magnitude is M6.93 which is close to M7.0 and so M7.0 may be used. The finding for Vancouver should not be extrapolated to other locations without checking whether it is appropriate. For example the mean magnitude for Chilliwack is M6.68 and using M7.0 would be too severe. The mean magnitude for Courtenay is M7.75 so M7.0 would underestimate the liquefaction potential. The correct approach is get the site specific mean magnitude from the GSC and use it with the site specific PGA. The increase in mean magnitude in the NBCC2015 seismic hazard is due to the inclusion of the subduction earthquakes M8.5-M9.2 in the probabilistic assessment of seismic hazard.

Table 1 – Factors of safety against liquefaction in Vancouver for various triggering options and NBCC2015 proposed ground motions.

SPT Blow-Count $(N_1)_{60}$	Current Practice (M7.0, 0.367g)	Mean Magnitude (M6.9, 0.367g)	Magnitude Deaggregation Method
10	0.41	0.42	0.43
13	0.48	0.50	0.51
15	0.54	0.56	0.57
18	0.64	0.66	0.67
20	0.72	0.74	0.75
25	1.02	1.05	1.07
30	1.73	1.78	1.80

2. Consequences of Liquefaction in Terms of Ground Displacements

Broadly speaking there are two approaches in common use for estimating the amount of lateral spreading in liquefiable ground, once the possibility of flow failure is eliminated. The first class of methods is exemplified by Youd et al. (2002), who assembled a database of lateral spreading observations and developed regression equations for predicting lateral spreading based on geotechnical profile information and the magnitude and distance of the triggering event. The second class of methods uses laboratory data from simple shear testing and shake table testing to arrive at cyclic strain limits once liquefaction is triggered in materials of various initial densities (i.e. field penetration resistance). The lateral displacements are then calculated from the strains. Idriss and Boulanger (2008, pp. 133-135) give a very lucid description of the various shear strain based methods. Only the Youd et al. (2002) approach is considered here as research on the application of the NBCC2015 ground motions to the other methods is still ongoing.

2.1. Youd et al. (2002) model

Youd et al. (2002) developed the predictive relationship for displacement described by Equation 2.

$$\log D_H = b_0 + b_1 M_w + b_2 \log R^* + b_3 R + b_4 \log W + b_5 \log S + b_6 \log T_{15} + b_7 \log(100 - F_{15}) + b_8 \log(D50_{15} + 0.1\,\text{mm}) \tag{2}$$

where D_H = horizontal displacement in meters and $R^* = R + 10^{(0.89Mw-5.64)}$. The values of the coefficients are given in Youd et al. (2002). Youd et al. (2002) also give a range of allowable variable values (of T_{15}, M_w, F_{15}, $D50_{15}$, W and S) for use in their predictive equation. The results of any analyses based on parameters that lie outside these ranges should be used with caution. For given site conditions, the lateral spreading depends on the moment magnitude, M_w, and R. Youd et al. (2002) provide the chart shown in Figure 4 for obtaining the equivalent distance, R. This chart is based on the average PGA from three different attenuation relations: Abrahamson and Silva 1997; Boore et al. 1997; and Campbell 1997. The average site acceleration is to be used in this chart, not the peak probabilistic acceleration (although the chart inadvertently states 'peak' PGA in the axis label).

2.2. Lateral displacements based on magnitude-distance deaggregation

When dealing with probabilistic ground motions in BC a magnitude M7.0 is selected and paired with a peak probabilistic ground motion selected from either a hazard analysis or from a site response analysis using input motions which match the probabilistic design spectrum over an appropriate period range. This probabilistic acceleration is made up of the average site acceleration plus εσ, where σ is the standard deviation and ε is the number of standard deviations required to reach the probabilistic value**.** The average acceleration at the site that is required for entry in Figure 4 may be obtained by running a seismic hazard analysis for the site with ε=0. The average acceleration for Vancouver is approximately 0.20g. Using the full probabilistic acceleration in the Figure 4 to obtain the equivalent distance for use in Equation 2, results in overly short distances and consequently, inflated estimates of displacement. It is imperative to use the average acceleration with Youd's chart.

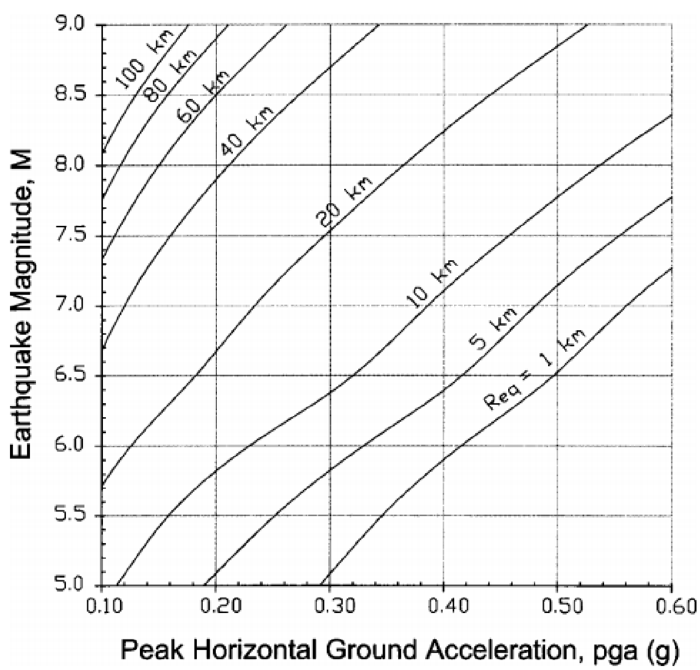

Fig. 4 - Graph for determining equivalent source distance, R_{eq}, for magnitude, M, and peak acceleration, a_{max} (after Youd et al. (2002)).

2.2.1 Average acceleration method

The lateral spreading displacement at a site may be estimated from Equation 2 by using the mean earthquake magnitude and the average acceleration.

2.1.2 Magnitude distance deaggregation method

The magnitude-distance deaggregation method used in evaluating liquefaction potential may also be used to evaluate lateral spreading displacements. For each magnitude-distance pair in the deaggregation matrix, we compute the corresponding lateral displacements using Youd's Equation 2. These displacements are multiplied by the per cent contribution of each magnitude to the site acceleration. This results in a spreadsheet of lateral displacement values. The displacements corresponding to any magnitude bin are summed horizontally over the distances and then the sums at the end of each row are summed to give the total horizontal displacement.

The spreadsheet of displacement calculations used in the deaggregation method are shown in Figure 5. Cells that show zero values represent extremely small displacements that are omitted for clarity. This spreadsheet also shows the clear separation of the contributions of the smaller and shallower earthquakes compared to the larger subcrustal earthquakes. Notice that influence of the latter kick in at distances of greater than 50km. The contributions of the subduction events become visible for magnitudes greater than M8.0 and at distances greater the 120km. Because of the scale of the spread sheet the subduction data cannot be shown here.

The typical deaggregation available on the GSC website (nrcan.gc.ca) is not suitable for this calculation because the distance bins are too large. If requesting a magnitude-distance deaggregation from GSC for lateral spreading calculations, specify a distance bin size of 5km.

Magnitude Bins	Distance Bins: 2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5		297.5	Row Totals:
5.1	0	0.0001	0	0	0	0	0	0	0	0	0	0	0	0		0	1E-04
5.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
5.5	0	0.0001	0	0	0	0	0	0	0	0	0	0	0	0		0	1E-04
5.7	0	0.0002	0.0002	0	0	0	0	0	0	0	0	0	0	0		0	4E-04
5.9	0	0.0003	0.0004	0	0	0	0	0	0	0	0	0	0	0		0	7E-04
6.1	0	0.0005	0.0007	0.0002	0	0	0	0	0	0	0	0	0	0		0	0.001
6.3	0	0.0008	0.0014	0.0005	0.0002	0	0	0	0	0	0	0	0	0		0	0.003
6.5	0	0.0012	0.0025	0.0013	0.0004	0.0002	0	0	0	0	0.0001	0.0001	0	0		0	0.006
6.7	0	0.0016	0.0038	0.0028	0.0011	0.0005	0.0003	0.0001	0	0	0.0005	0.0005	0.0004	0.0002		0	0.012
6.9	0	0.0021	0.0052	0.0053	0.0025	0.0012	0.0006	0.0003	0.0002	0	0.0015	0.0017	0.0013	0.0008		0	0.024
7.1	0	0.0026	0.0068	0.0079	0.005	0.0027	0.0015	0.0008	0.0005	0.0002	0.0028	0.0034	0.0028	0.0019		0	0.042
7.3	0	0.0029	0.0083	0.0103	0.0082	0.0055	0.0035	0.0018	0.0012	0.0006	0.0013	0.0014	0.0012	0.0009		0	0.049
7.5	0	0.0013	0.0041	0.0053	0.0045	0.0037	0.0029	0.0017	0.0011	0.0006	0.0013	0.0015	0.0013	0.001		0	0.033
7.7	0	0.0002	0.0006	0.0008	0.0007	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0	0	0		0	0.004
7.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.002
8.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.009
8.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.035
																Total of the Totals:	0.221

Fig. 5 – Sample calculation of lateral spreading displacements using the deaggregation method

Both methods are applied to a school project site in Delta, BC to evaluate the lateral spreading displacements. The probabilistic PGA was 0.395g. The site parameters are as follows: average ground slope, S = 0.5%, $D50_{15}$ = 0.25mm, F_{15} = 5% and T_{15} varies with location at the site. The T_{15} values for the six site locations are 8.60m, 8.80m, 7.75m, 9.95m, 4.95m and 7.95m, respectively (as reported in the geotechnical site investigation report).

The lateral spreading displacements are calculated using Equation 2 using local practice. For M7.0, a_{max}=0.395g, Figure 4 yields an approximate distance R≈9km. Computed displacements using Equation 2 with M7.0 and R≈9km of up to 2m are shown in olive green in Figure 6.

The displacements are also calculated using the mean magnitude M6.93 and the average acceleration of 0.20g, which gives a distance R=26km. The displacements d are shown in bright green in Figure 6. The results from a full deaggregation analysis are shown in purple in Figure 6. The two methods give approximately the same levels of displacement. It is clear that using the probabilistic peak ground acceleration to determine the equivalent distance for use in the Youd Equation gives inflated estimates for lateral spreading displacement.

As can also be seen in Figure 6, the displacements computed using the deaggregation method and the average acceleration method are approximately 20% of the Youd et al. (2002) displacements. The difference with the Youd displacements is a result of the probabilistic acceleration, rather than the average acceleration, being used to calculate the displacements.

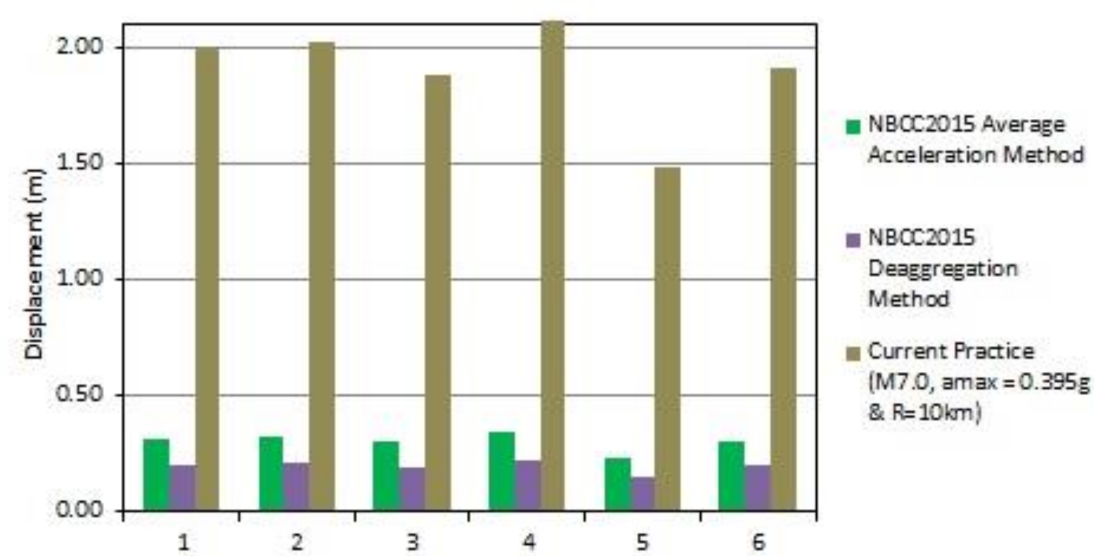

Fig. 6 – Calculated displacements for the school site in Delta, BC

2.2.1. Differences in lateral spreading displacements calculated using NBCC2010 and NBCC2015

Figure 7 compares the displacements obtained by applying the two methods proposed using the NBCC2010 and NBCC2015 hazard levels. The 'Current Practice' predictions for NBCC2015 are included for comparison. The changes to the NBCC between 2010 and 2015 resulted in a lower PGA and so lower lateral displacements, provided the correct acceleration is used in Figure 4 to obtain R.

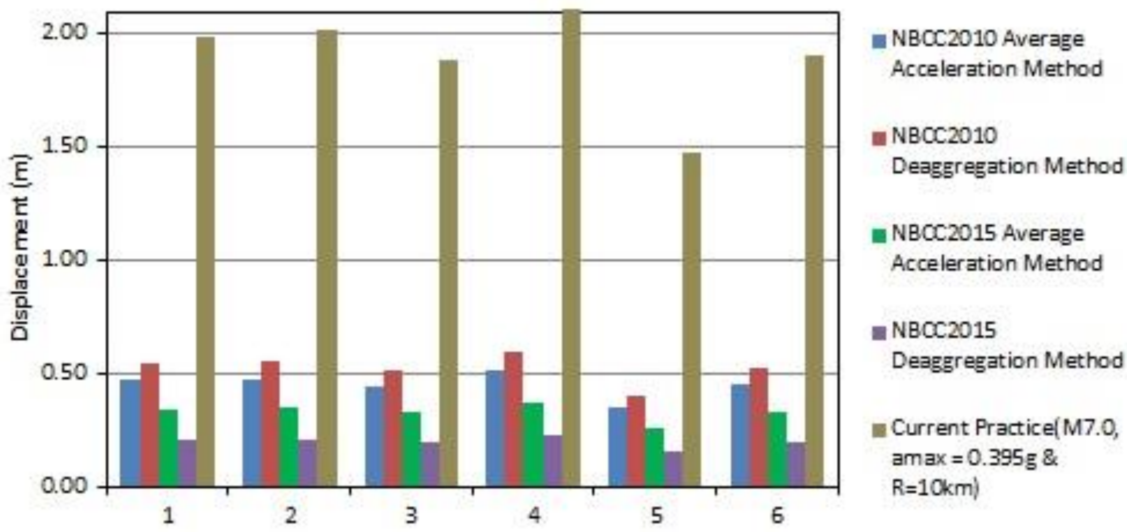

Fig. 7 – Differences in lateral spreading displacements for school site in Delta using NBCC2010 and NBCC2015

3. Conclusions

This paper describes methods for the estimation of liquefaction potential and lateral spreading displacements, when the seismic hazard is specified by probabilistic ground motions. Two methods are proposed for estimating liquefaction potential; a deaggregation method and an average magnitude method. It has been demonstrated that both methods give approximately the same answer, therefore the simpler average magnitude approach is recommended for practice. The average magnitude can be obtained from the GSC website (nrcan.gc.ca). Two methods are also proposed for estimating the lateral spreading using the Youd et al. (2002) approach; a deaggregation method similar to that used for assessing liquefaction potential and an average acceleration method. The deaggregation method requires a much finer distance sampling for displacement analysis, typically about 5km. The average acceleration method uses the mean magnitude and the average acceleration to estimate the displacement in a one step approach. The average acceleration can be obtained by a site specific hazard analysis. The average acceleration method gives approximately the same result as the deaggregation method.

4. Acknowledgements

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