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Influence of corrections to recorded peak ground accelerations due to liquefaction on predicted liquefaction response during the M_w 6.2, February 2011 Christchurch earthquake.

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ABSTRACT: Evaluations of Liquefaction Potential Index (LPI) in the 2010-2011 Canterbury earthquake sequence (CES) in New Zealand have shown that the severity of surficial liquefaction manifestations is significantly over-predicted for a large subset of sites. While the potential cause for such over-predictions has been generally identified as the presence of thick, non-liquefiable crusts and/or interbedded non-liquefiable layers in a soil profile, the severity of surficial liquefaction manifestations at sites that do not have such characteristics are also often significantly over-predicted, particularly for the M_w 6.2, February 2011 Christchurch earthquake. The over-predictions at this latter group of sites may be related to the peak ground accelerations (PGAs) used in the liquefaction triggering evaluations. In past studies, the PGAs at the case history sites were estimated using a procedure that is conditioned on the recorded PGAs at nearby strong motion stations (SMSs). Some of the soil profiles on which these SMSs were installed experienced severe liquefaction, often with an absence of surface manifestation, and the recorded PGAs are inferred to be associated with high-frequency dilation spikes after liquefaction was triggered. Herein the influence of using revised PGAs at these SMSs that are in accord with pre-liquefaction motions on the predicted severity of surficial liquefaction at nearby sites is investigated. It is shown that revising the PGAs improved these predictions, particularly at case history sites where the severity of the surface manifestations was previously over-predicted and could not be explained by other mechanisms.

1 INTRODUCTION

The 2010-2011 Canterbury, New Zealand, earth-quake sequence (CES) began with the 4 September 2010, M_w 7.1 Darfield earthquake and included up to ten events that triggered liquefaction. However, most notably, widespread liquefaction was induced by the M_w 7.1, 4 September 2010 Darfield and the M_w 6.2, 22 February 2011 Christchurch earthquakes. The ground motions from these events were recorded across Christchurch and its environs by a dense network of strong motion stations (SMSs). Also, due to the severity and spatial extent of liquefaction resulting from the 2010 Darfield earthquake, the New Zealand Earthquake Commission (EQC) funded an extensive subsurface characterization program for Christchurch, with over 25,000 Cone Penetration Tests (CPT) performed to date. The combination of well-documented liquefaction response during multiple events, densely-recorded ground motions for the events, and detailed subsurface characterization provided an unprecedented opportunity to investigate liquefaction triggering and related phenomena. Towards this end, multiple studies have investigated the accuracy of various liquefaction triggering evaluation procedures and liquefaction severity index models (e.g., Green et al. 2014, 2015; Maurer et al. 2014, 2015; van Ballegooy et al. 2014b). Among others, Maurer et al. (2014, 2015) evaluated the performance of the Liquefaction Potential Index (LPI) (Iwasaki et al. 1978) during the 2010-2011 CES and found that it systematically over-predicted the severity of surficial liquefaction manifestations for a significantly large number of sites. Moreover, Maurer et al. (2014, 2015) found that such over-predicted case histories generally were comprised of soil profiles having thick, non-liquefiable crusts and/or interbedded non-liquefiable soils high in fines content, which could have suppressed the surficial manifestation of liquefied layers. However, the severity of surficial liquefaction manifestations was also over-predicted for a number of soil profiles that do not have these characteristics, especially for the M_w 6.2, February 2011 Christchurch earthquake.

One reason for these latter over-predictions may be related to the peak ground accelerations (PGAs) used in the liquefaction triggering evaluations. The PGAs at CPT sites in most prior CES studies have been estimated using the Bradley (2013b) procedure, which combines the unconditional PGA distribution as estimated by the Bradley (2013a) ground motion prediction equation, the recorded PGAs at the SMSs, and the spatial correlations of intra-event residuals to compute the conditional PGAs at sites of interest. Thus, for sites that are located far enough away from an SMS, the conditional PGAs are similar to the unconditional PGAs, and for the sites that are located near an SMS, the PGAs approach the recorded PGA at the SMS. However, the soil profiles at some of the SMSs were found to have severely liquefied during the 2011 Christchurch earthquake, as evidenced by the cyclic mobility/dilation spikes and reduced high frequency content of the horizontal components of the recorded ground motions after liquefaction was triggered (Bradley & Cubrinovski 2011). Thus, the recorded PGAs at these SMSs typically corresponded to the amplitude of these high-frequency dilation spikes, which are often higher than the PGAs of the pre-liquefaction portion of the ground motions and likely higher than the PGAs that would have been experienced at the sites if liquefaction had not been triggered. Wotherspoon et al. (2014, 2015) identified four such SMSs where the recorded PGAs were higher than the pre-liquefaction PGAs and suggested reduced PGAs for those SMSs, as summarized in Table 1. An example acceleration time history at the North New Brighton School (NNBS) SMS is also shown in Figure 1, which indicates the cyclic mobility/dilation spikes caused by the liquefaction of the underlying soils and the interpreted pre-liquefaction PGA.

Table 1. Revised PGA values at four SMSs for M_w 6.2, February 2011 Christchurch earthquake as recommended by Wotherspoon et al. (2015).

SMS Name	SMS ID	PGA (g)	
		Recorded	Revised
Christchurch Botanical Gardens	CBGS	0.50	0.32
Christchurch Cathedral College	CCCC	0.43	0.35
North New Brighton School	NNBS	0.67	0.32
Christchurch Resthaven	REHS	0.52	0.36

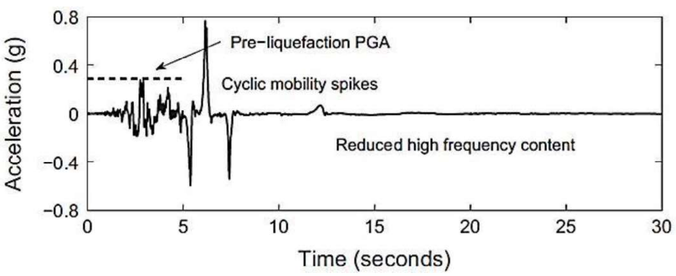

Figure 1. Ground motion record at NNBS during the M_w 6.2 Christchurch earthquake showing cyclic mobility/dilation spikes and the pre-liquefaction PGA (Wotherspoon et al. 2015).

Accordingly, the objective of this study is to investigate the influence of using the pre-liquefaction PGA at the SMSs on the predicted severity of surficial liquefaction manifestations at nearby case history sites during the 2011 Christchurch earthquake. Towards this end, the PGAs for a select group of case history sites that are located close to the SMSs listed in Table 1 are estimated following the Bradley (2013b) procedure, using both the actual recorded PGAs and the pre-liquefaction PGAs at the SMSs. Both sets of PGAs are then used to predict the severity of surficial liquefaction manifestations via LPI and the prediction accuracies are assessed.

2 DATA AND METHODOLOGY

As discussed previously, revising the PGAs at the four SMSs listed in Table 1 to the pre-liquefaction PGAs mostly affects nearby sites. Thus, only CPT soundings that are located within 1 km from at least one of the four SMSs listed in Table 1 are analyzed in this study. Maurer et al. (2015) found that sites with an average soil-behavior-type index (I_c) for the upper 10 m of the soil profile (I_{c10}) less than 2.05 generally correspond to sites having predominantly clean sands to silty sands. Thus, only soundings that have $I_{c10} < 2.05$ were considered in this study, with the intent of removing cases where the over-predictions are potentially due to other causes (e.g., interbedded non-liquefiable layers high in fines content). Using all of the above criteria, 416 CPT soundings were selected for further analysis.

The severity of surficial liquefaction manifestation at each of the 416 CPT sounding locations for the 2011 Christchurch earthquake was classified in accordance with Green et al. (2014) via post-earthquake ground reconnaissance and high-resolution aerial and satellite imagery. The CPT soundings and imagery were extracted from the New Zealand Geotechnical Database (NZGD 2016). The PGA at the site of each CPT sounding was estimated using two different approaches: a) the Bradley (2013b) procedure in conjunction with the actual recorded PGAs at the SMSs, similar to prior CES studies; and (b) the Bradley (2013b) procedure in conjunction with the revised pre-liquefaction PGAs at four SMSs (see Table 1). The PGAs at the selected case history sites resulting from approaches (a) and (b) are referred to herein as "existing" PGAs and "new" PGAs respectively. The depth of ground water table immediately prior to the earthquake was estimated using the event-specific model of van Ballegooy et al. (2014a). Finally, LPI was computed for each site using both sets of PGAs, where the factor of safety against liquefaction (FS_{liq}) was computed using the Boulanger & Idriss (2014) deterministic liquefaction evaluation procedure (LEP). Inherent to this process, soils with $I_c > 2.5$ were considered to be non-liquefiable (Maurer et al. 2017, 2018).

The accuracy of LPI predictions for both sets of PGAs were assessed following the procedure used by Maurer et al. (2014), in which ranges of LPI values assigned to different categories of surficial liquefaction manifestation severity (e.g., Table 2) are used to compute an error (E), where E = computed LPI – (min or max) of expected range (i.e. min if computed LPI is less than the lower limit of the expected range and max if computed LPI is higher than the upper limit of the expected range). For example: if the computed LPI is 20 for a site with no observed surficial liquefaction manifestations, E = 20 - 4 = 16. Similarly, if the computed LPI is 7 for a site with severe surficial manifestations, E = 7 - 15 = -8. The prediction errors are then classified into one of the nine categories as shown in Table 3. Note that although Maurer et al. (2014) suggested the LPI ranges shown in Table 2 based on the Robertson & Wride (1998) LEP, they were generally found to be applicable in this study as well, which uses the Boulanger & Idriss (2014) LEP.

Table 2. LPI ranges used to assess the prediction accuracy (Maurer et al. 2014).

Manifestation severity category	Expected LPI range
No liquefaction	$0 \leq LPI < 4$
Marginal liquefaction	$4 \leq LPI < 8$
Moderate liquefaction	$8 \leq LPI < 15$
Severe liquefaction	$LPI \geq 15$

Table 3. LPI prediction error classification (Maurer et al. 2014).

Error category	Prediction error (E)
Excessive under-prediction	$E < -15$
Severe to excessive under-prediction	$-15 \leq E < -10$
Moderate to severe under-prediction	$-10 \leq E < -5$
Slight to moderate under-prediction	$-5 \leq E < -1$
Accurate prediction	$-1 \leq E < 1$
Slight to moderate over-prediction	$1 \leq E < 5$
Moderate to severe over-prediction	$5 \leq E < 10$
Severe to excessive over-prediction	$10 \leq E < 15$
Excessive over-prediction	$E > 15$

3 RESULTS AND DISCUSSIONS

Table 4 summarizes the number of case histories in each error category resulting from using the two sets of PGAs (i.e. existing and new PGAs). Moreover, histograms of these results are presented in Figure 2.

It can be seen that using the new PGAs decreased the total number of over-predictions (i.e. "Slight to moderate O-P" to "Excessive O-P) from 262 to 56. However, the new PGAs also increased the number of under-predictions (i.e. "Slight to moderate U-P" to "Excessive U-P") from 13 to 90, but these were mostly slight-to-moderate under-predictions. Moreover, the rate at which the over-predictions changed to accurate predictions is significantly higher than the rate at which the accurate prediction changed to under-predictions. Overall, the number of accurate pre-dictions increased from 141 to 270.

These findings suggest that corrections to the recorded PGAs for SMS sites that experience liquefaction is warranted in evaluating liquefaction procedures or documenting liquefaction case histories. Specifically, the high frequency cyclic mobility/dilation spikes after liquefaction triggering can result in over-estimated PGA values (hence, overly conservative seismic demand) for liquefaction triggering evaluations, which in turn can lead to over-predictions of the severity of surficial liquefaction manifestations. The revised PGAs used in this study were proposed by Wotherspoon et al. (2104, 2015) and corresponded to the PGAs of the recorded motions prior to the onset of liquefaction, where judgement was used to determine the timing of liquefaction triggering. More formal approaches for determining this timing are under development (e.g., Kramer et al. 2016, 2018).

An example case history is presented next that illustrates the influence of using the pre-liquefaction PGA at a nearby SMS on the predicted severity of surficial liquefaction manifestation.

Table 4. Summary of number of case histories in each error category using the existing and new PGAs.

Error category	Number of Case Histories	
	existing PGA	new PGA
Excessive U-P	0	0
Severe to excessive U-P	0	1
Moderate to severe U-P	4	14
Slight to moderate U-P	9	75
Accurate Prediction	141	270
Slight to moderate O-P	81	39
Moderate to severe O-P	104	11
Severe to excessive O-P	54	2
Excessive O-P	23	3
Total U-P	13	90
Total O-P	262	56

U-P = Under-predictions; O-P = Over-predictions

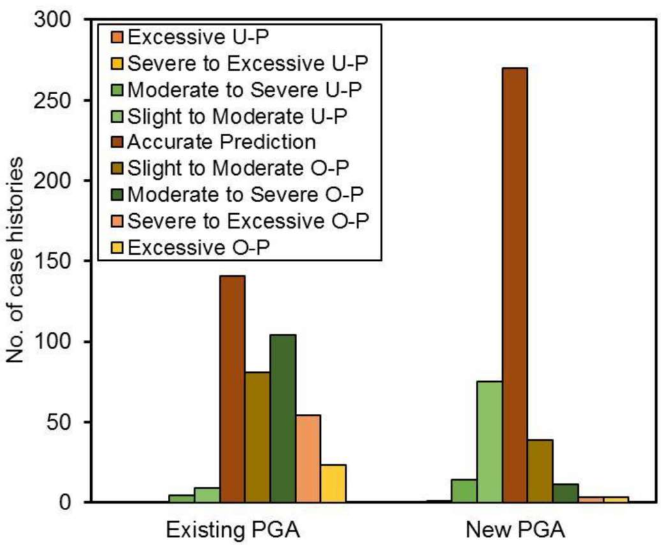

Figure 2. Histogram showing the number of case histories in each error category using the existing and new PGAs.

Case History Site: NNB-POD03-CPT05

This case history site is located ~0.4 km from the NNBS SMS and is predominantly comprised of clean sands, as inferred from the I_c profile (Fig. 3). The PGA estimated at this site during the M_w 6.2, February 2011 Christchurch earthquake prior to making any adjustments to the recorded PGAs was 0.531 g. The depth to the ground water table was estimated to be approximately 2 m. No evidence of surficial liquefaction manifestation was observed at this site following the 2011 Christchurch earthquake. However, the LPI value computed using the existing PGAs was 13, which corresponds to expected moderate surface manifestation. Thus, the severity of surficial liquefaction manifestation is over-predicted at this site and the prediction error is moderate-to-severe over-prediction (e.g. Table 3). The new PGA estimated at this site using the revised (pre-liquefaction) PGAs at the SMSs was 0.334 g. The computed LPI value associated with this new PGA was 2 which corresponds to no surficial liquefaction manifestations. Thus, it is seen that using the pre-liquefaction PGA at the SMSs to compute the PGA at this site corrected the prediction of the severity of surficial liquefaction manifestation at this site.

Figure 3 contains the profiles of normalized and fines-content corrected CPT tip resistance (q_{c1Ncs}) and I_c for the case history site, as well as the profiles of FS_{liq} and LPI computed using both the existing and new PGAs.

4 CONCLUSIONS

This study investigated the influence of revising the recorded PGAs at the liquefied SMSs to the PGA of the pre-liquefaction portion of the ground motion on the predicted severity of surficial liquefaction at nearby sites. By analyzing 416 case-history sites located within 1 km of such SMSs, it was shown that using the new PGAs estimated by revising the PGAs at the SMSs correctly predicted a significant number of case histories that were previously over-predicted, likely due to over-estimated PGAs. Finally, the findings of this study highlight the need to accurately estimate PGAs for liquefaction evaluation by accounting for the effects that liquefaction of the underlying soils may have on recorded ground motions.

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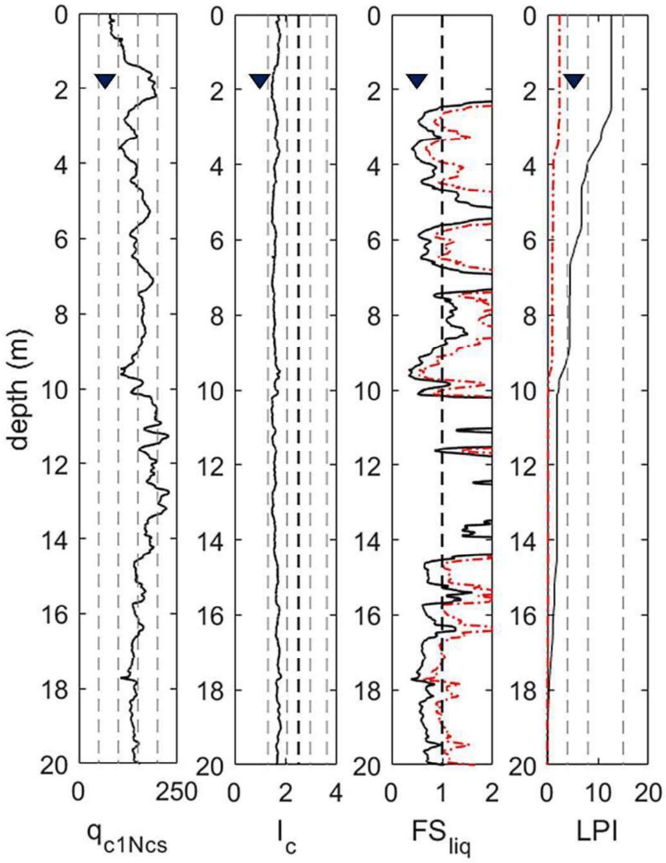

Figure 3. Profiles of q_{c1Ncs}, I_c, FS_{liq}, and LPI versus depth for NNB-POD03-CPT05 for the M_w 6.2 February 2011 Christchurch earthquake. The solid black and red dotted lines on the profiles of FS_{liq} and LPI correspond to the existing and new PGAs at the site.

REFERENCES

Boulanger, R.W. & Idriss, I.M. 2014. *CPT and SPT based liquefaction triggering procedures*. Report No. UCD/CGM. -14/01, Center for Geotechnical Modelling, Department of Civil and Environmental Engineering, UC Davis, CA, USA.

Bradley, B.A. 2013a. A New Zealand-specific pseudo-spectral acceleration ground-motion prediction equation for active shallow crustal earthquakes based on foreign models. *Bulletin of the Seismological Society of America* 103(3): 1801-1822.

Bradley, B.A. 2013b. Site-Specific and spatially-distributed ground motion intensity estimation in the 2010-2011 Christ-church earthquakes. *Soil Dynamics and Earthquake Engineering* 48: 35-47.

Bradley, B.A. & Cubrinovski, M. (2011). Near-source Strong Ground Motions Observed in the 22 February 2011 Christchurch Earthquake. *Seismological Research Letters* 82: 853-865.

Green, R.A., Cubrinovski, M., Cox, B., Wood, C., Wotherspoon, L., Bradley, B. & Maurer, B.W. 2014. Select liquefaction case histories from the 2010-2011 Canterbury earthquake sequence. *Earthquake Spectra* 30(1): 131-153.

Green, R.A., Maurer, B.W., Cubrinovski, M. & Bradley, B.A. 2015. Assessment of the Relative Predictive Capabilities of CPT-Based Liquefaction Evaluation Procedures: Lessons Learned from the 2010-2011 Canterbury Earthquake Sequence. *Proc. 6th Intern. Conf. on Earthquake Geotechnical*

Engineering (6ICEGE), Christchurch, New Zealand, 2-4 November.
Iwasaki, T., Tatsuoka, F., Tokida, K. & Yasuda, S. 1978. A practical method for assessing soil liquefaction potential based on case studies at various sites in Japan. *Proceedings of the 2nd International Conference on Microzonation,* Nov 26-Dec 1, San Francisco, CA, USA.
Kramer, S.L., Sideras, S.S. & Greenfield, M.W. 2016. The timing of liquefaction and its utility in liquefaction hazard evaluation. *Soil Dynamics and Earthquake Engineering 91:133-146.*
Kramer, S.L., Sideras, S.S., Greenfield, M.W. & Hushmand, B. 2018. Liquefaction, ground motions, and pore pressures at the Wildlife Liquefaction Array in the 1987 Superstition Hills earthquake. *Proc. Geotechnical Earthquake Engineering and Soil Dynamics V* (GEESD V), *Liquefaction Triggering, Consequences, and Mitigation* (S.J. Brandenberg and M.T. Manzari, eds.), ASCE Geotechnical Special Publication (GSP) 290: 384-402.
Maurer, B.W., Green, R.A., Cubrinovski, M. & Bradley, B.A. 2014. Evaluation of the liquefaction potential index for assessing liquefaction hazard in Christchurch, New Zealand. *Journal of Geotechnical and Geoenvironmental Engineering* 140(7): 04014032.
Maurer, B.W., Green, R.A., Cubrinovski, M. & Bradley, B.A. 2015. Fines-content effects on liquefaction hazard evaluation for infrastructure during the 2010-2011 Canterbury, New Zealand earthquake sequence. *Soil Dynamics and Earthquake Engineering* 76: 58-68.
Maurer, B.W., Green, R.A., van Ballegooy, S. & Wotherspoon, L. 2017. Assessing Liquefaction Susceptibility Using the CPT Soil Behavior Type Index. *Proc. 3rd Intern. Conf. on Performance-Based Design in Earthquake Geotechnical Engineering* (PBDIII), Vancouver, Canada, 16-19 July.
Maurer, B.W., Green, R.A., van Ballegooy, S. & Wotherspoon, L. 2018. Development of Region-Specific Soil Behavior Type Index Correlations for Evaluating Liquefaction Hazard in Christchurch, New Zealand. *Soil Dynamics and Earth-quake Engineering* (*in press*)
NZGD 2016. *New Zealand Geotechnical Database*. <https://www.nzgd.org.nz/Default.aspx> Accessed 8/24/16. New Zealand Earthquake Commission (EQC).
Robertson, P.K. & Wride, C.E. 1998. Evaluating cyclic liquefaction potential using cone penetration test. *Canadian Geotechnical Journal* 35(3): 442-459.
van Ballegooy, S., Cox, S.C., Thurlow, C., Rutter, H.K., Reynolds T., Harrington, G., Fraser, J. & Smith, T. 2014a. *Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield earthquake: Version 2*. GNS Science Report 2014/18.
van Ballegooy, S., Malan, P., Lacrosse, V., Jacka, M.E., Cubrinovski, M., Bray, J.D., O'Rourke, T.D., Crawford, S.A. & Cowan, H. 2014b. Assessment of liquefaction-induced land damage for residential Christchurch. *Earthquake Spectra* 30(1): 31-55.
Wotherspoon, L.M, Orense, R.P, Bradley, B.A., Cox, B.R., Wood, C. & Green, R.A. 2014. *Geotechnical characterisation of Christchurch strong motion stations*, Earthquake Commission Biennial Grant Report; 2014, project no. 12/629.
Wotherspoon, L.M., Orense, R.P., Green, R.A., Bradley, B.A., Cox, B.R. & Wood, C.M. 2015. Assessment of liquefaction evaluation procedures and severity index frameworks at Christchurch strong motion stations. *Soil Dynamics and Earthquake Engineering* 79(Part B): 335–346.