



Assessing the Limitations of Liquefaction Manifestation Severity Index Prediction Models

Russell A. Green¹(✉), Sneha Upadhyaya¹, Brett W. Maurer²,
and Adrian Rodriguez-Marek¹

¹ Virginia Tech, Blacksburg, VA 24061, USA

{rugreen,usneha,adrianrm}@vt.edu

² University of Washington, Seattle, WA 98195, USA

bwmaurer@uw.edu

Abstract. The severity of surface manifestation of liquefaction is commonly used as a proxy for liquefaction damage potential. As a result, manifestation severity index (MSI) models are more commonly being used in conjunction with simplified stress-based triggering models to predict liquefaction damage potential. This paper assesses the limitations of four MSI models. The different models have differing attributes that account for factors influencing the severity of surficial liquefaction manifestations, with the newest of the proposed models accounting more factors than the others. The efficacies of these MSI models are evaluated using well-documented liquefaction case histories from Canterbury, New Zealand, with the deposits primarily comprising clean to non-plastic silty sands. It is found that the MSI models that explicitly account for the contractive/dilative tendencies of soil did not perform as well as the models that do not account for this tendency, opposite of what would be expected based on the mechanics of liquefaction manifestation. The likely reason for this is the double-counting of the dilative tendencies of medium-dense to dense soils by these MSI models, since the liquefaction triggering model, to some extent, inherently accounts for such effects. This implies that development of mechanistically more rigorous MSI models that are used in conjunction with simplified triggering models will not necessarily result in improved liquefaction damage potential predictions and may result in less accurate predictions.

Keywords: Liquefaction triggering · Liquefaction severity · Liquefaction surficial manifestations

1 Introduction

The objective of this study is to assess the limits of predicting the occurrence and severity of surficial liquefaction manifestation via manifestation severity index (MSI) models that are used in conjunction with simplified stress-based triggering models. An accurate prediction of the severity of surficial liquefaction manifestation is critical for reliably assessing the risk due to liquefaction. This requires a proper understanding of the mechanics of the manifestation of surficial liquefaction features and the controlling factors.

Different models have been proposed in the literature to predict the occurrence/severity of surficial liquefaction manifestation (i.e., MSI models). These models use the results from simplified stress-based liquefaction triggering models and tie the cumulative response of the soil profile to the occurrence/severity of surficial liquefaction manifestation. One of the earliest MSI models is the Liquefaction Potential Index (*LPI*), proposed by Iwasaki et al. [1]. While *LPI* has been widely used to characterize the damage potential of liquefaction throughout the world, it was found to perform inconsistently during the 2010–2011 Canterbury earthquakes in New Zealand (e.g., [2–4]). This inconsistency can be attributed to limitations in the *LPI* formulation to appropriately account for some of the factors influencing surficial manifestation of liquefaction. Specifically, the *LPI* formulation may not adequately account for the contractive/dilative tendencies of the soil on the potential consequences of liquefaction. Additionally, the *LPI* formulation does not account for the limiting thickness of the non-liquefied crust and/or the effects of non-liquefiable, high fines-content (*FC*), high-plasticity strata on the severity of surficial liquefaction manifestations. Although the influence of these effects could be accounted for by using different *LPI* manifestation severity thresholds (i.e., *LPI* values distinguishing between different manifestation severity classes, e.g., [3, 5]), it is preferred to have a model that can explicitly account for these conditions in a less ad hoc manner.

In efforts to address some of the shortcomings in the *LPI* formulation, alternative MSI models have been proposed, such as the Ishihara-inspired *LPI* (*LPI_{ish}*) [6] and Liquefaction Severity Number (*LSN*) [7]. A major improvement of *LPI_{ish}* over *LPI* is that it explicitly accounts for the phenomenon of limiting-crust-thickness, where a non-liquefied capping stratum having an equal or greater thickness than the limiting crust thickness inhibits any surficial liquefaction manifestations regardless of the liquefaction response of the underlying strata. This attribute of the *LPI_{ish}* model is derived from Ishihara's [8] empirical relationship that relates the thicknesses of the non-liquefied crust (H_1) and of the liquefied stratum (H_2) to the occurrence of surficial liquefaction manifestations. However, as with *LPI*, *LPI_{ish}* does not explicitly account for the contractive/dilative tendencies of the soil on the severity of manifestations. The *LSN* formulation conceptually overcomes this limitation of *LPI*, as well as *LPI_{ish}*, in that it explicitly accounts for the additional influence of contractive/dilative tendencies of the soil via a relationship among *FS*, D_r , and the post-liquefaction volumetric strain potential (ε_v) [9]. However, *LSN* does not account for the phenomenon of limiting-crust-thickness, as *LPI_{ish}* does.

Based on the identified limitations of previously proposed MSI models, Upadhyaya et al. [10] proposed a new MSI model that accounts for the limiting-crust-thickness phenomenon and the effects of contractive/dilative tendencies of the soil on the severity of surficial liquefaction manifestations is proposed. The new model, termed *LSN_{ish}*, combines the positive attributes of *LPI_{ish}* and *LSN* in a single formulation that mechanistically accounts for the limiting-crust-thickness phenomenon based on Ishihara's H_1 - H_2 boundary curves and the contractive/dilative tendencies of the soil on the severity of surficial liquefaction manifestation via an *FS*- D_r - ε_v relationship [9]. Similar to the derivation of *LPI_{ish}* [6], the new index is a conceptual and mathematical merger of the Ishihara [8] H_1 - H_2 relationships and the *LSN* formulation. In the following, overviews

of LPI , LPI_{ish} , LSN , and LSN_{ish} models are presented first. Next, these four MSI models are evaluated using a large dataset of liquefaction case histories from the 2010–2011 Canterbury earthquake sequence and the 2016 Valentine’s Day earthquake that impacted Christchurch, New Zealand, and the MSI models’ predictive efficiencies are assessed.

2 Overview of MSI Models

2.1 Liquefaction Potential Index (LPI)

The liquefaction potential index (LPI) is defined as [1]:

$$LPI = \int_0^{z_{max}} F_{LPI}(FS) \cdot w_{LPI}(z) dz \quad (1)$$

where: FS is the factor of safety against liquefaction triggering, computed using a liquefaction triggering model; z is depth below the ground surface in meters; z_{max} is the maximum depth considered, generally 20 m; and $F_{LPI}(FS)$ and $w_{LPI}(z)$ are functions that account for the weighted contributions of FS and z on surface manifestation. Specifically, $F_{LPI}(FS) = 1 - FS$ for $FS \leq 1$ and $F_{LPI}(FS) = 0$ otherwise; and $w_{LPI}(z) = 10 - 0.5z$. Thus, LPI assumes that the severity of surface manifestation depends on the cumulative thickness of liquefied soil layers, the proximity of those layers to the ground surface, and the amount by which FS in each layer is less than 1.0.

2.2 Ishihara-Inspired Liquefaction Potential Index (LPI_{ish})

Using the data from the 1983, $M_w 7.7$ Nihonkai-Chubu and the 1976, $M_w 7.8$ Tangshan earthquakes, along with considerable judgement, Ishihara [8] proposed a generalized relationship relating the thicknesses of the non-liquefiable crust (H_1) and of the underlying liquefied strata (H_2) to the occurrence of liquefaction-induced damage at the ground surface. This relationship is presented in the form of boundary curves that separate cases with and without surficial liquefaction manifestation as a function of peak ground acceleration (a_{max}). The H_1 - H_2 boundary curves imply that, for a given a_{max} , there exists a limiting H_1 , thicker than which surficial liquefaction manifestations will not occur regardless of the value of H_2 (i.e., the limiting-crust-thickness phenomenon mentioned in the Introduction). While Ishihara’s H_1 - H_2 curves have been shown to be conceptually correct, they are not easily implementable for more complex soil profiles that have multiple interbedded non-liquefied/non-liquefiable soil strata, such as those in Christchurch, New Zealand (e.g., [7, 11]). Additionally, the curves were derived from earthquakes that have a narrow magnitude range (i.e., $M_w 7.7$ – 7.8).

To account for the limiting-crust-thickness phenomenon on the severity of surficial liquefaction manifestations using a more quantitative approach, Maurer et al. [6] utilized Ishihara’s boundary curves to derive an alternative MSI model, LPI_{ish} :

$$LPI_{ish} = \int_{H_1}^{z_{max}} F_{LPI_{ish}}(FS) \cdot \frac{25.56}{z} dz \quad (2a)$$

where

$$F_{LPI_{ish}}(FS) = \begin{cases} 1 - FS & \text{if } FS \leq 1 \cap H_1 \cdot m(FS) \leq 3 \text{ m} \\ 0 & \text{otherwise} \end{cases} \quad (2b)$$

and

$$m(FS) = \exp\left[\frac{5}{25.56 \cdot (1 - FS)}\right] - 1; \quad m(FS > 0.95) = 100 \quad (2c)$$

where FS and z_{max} are defined the same as they are for LPI . The LPI_{ish} framework explicitly accounts for the limiting thickness of the non-liquefied crust by imposing a constraint on $F_{LPI_{ish}}(FS)$ and uses a power-law depth weighting function, which is consistent with Ishihara's H_1 - H_2 boundary curves. The power-law depth weighting function results in LPI_{ish} model giving a higher weight to shallower layers than the LPI model in predicting the severity of surficial liquefaction manifestations.

2.3 Liquefaction Severity Number (LSN)

As stated in the Introduction, LSN was proposed by van Ballegooy et al. [7] and uses a relationship relating FS , D_r , and ε_v to account for the contractive/dilative tendencies of the soil on the severity of surficial liquefaction manifestations [9]. LSN is given by:

$$LSN = \int_0^{z_{max}} 1000 \cdot \frac{\varepsilon_v}{z} dz \quad (3)$$

where z_{max} is the maximum depth considered, generally 10 m, and ε_v is estimated by using the relationship proposed by Zhang et al. [12] (entered as a decimal in Eq. 3), which is based on the FS - D_r - ε_v relationship proposed by Ishihara and Yoshimine [9]. Thus, unlike the LPI and LPI_{ish} models, which only consider the influence of soil strata with $FS < 1$ on the severity of surficial liquefaction manifestations, the LSN model considers the contribution of layers with $FS \leq 2$ via the FS - D_r - ε_v relationship [9].

2.4 Ishihara-Inspired LSN (LSN_{ish})

As mentioned previously, the LSN_{ish} model merges the positive attributes of the LPI_{ish} and LSN models. The derivation of the LSN_{ish} model follows a procedure similar to the derivation of the LPI_{ish} model [6] and is detailed in Upadhyaya et al. [10]. LSN_{ish} is given by:

$$LSN_{ish} = \int_{H_1}^{z_{max}} F_{LSN_{ish}}(\varepsilon_v) \cdot \frac{36.929}{z} \cdot dz \quad (4a)$$

where

$$F_{LSN_{ish}}(\varepsilon_v) = \begin{cases} \frac{\varepsilon_v}{5.5} & \text{if } FS \leq 2 \text{ and } H_1 \cdot m(\varepsilon_v) \leq 3m \\ 0 & \text{otherwise} \end{cases} \quad (4b)$$

and

$$m(\varepsilon_v) = \exp\left(\frac{0.7447}{\varepsilon_v}\right) - 1; m(\varepsilon_v < 0.16) = 100 \quad (4c)$$

where ε_v is expressed in percent. The LSN_{ish} model explicitly accounts for: (1) the influence of ε_v on the severity of surficial liquefaction manifestations; (2) the limiting-crust-thickness phenomenon; and (3) the contribution of liquefiable layers with $FS \leq 2$ to the severity of surficial liquefaction manifestations.

Specific to item (2), the limiting crust thickness is accounted for in the LSN_{ish} model via the requirement that $H_I \cdot m(\varepsilon_v) \leq 3$ m in Eq. 4b. Since m is a function of ε_v (which in turn is a function of normalized penetration resistance and FS), it is implied that as ε_v increases, the thickness of the non-liquefiable crust required to suppress manifestations increases. The limiting crust thickness is equal to 3 m/ m , where m is a function of the penetration resistance of the soil (e.g., normalized cone penetration tip resistance, q_{c1Ncs}) and FS against liquefaction triggering.

3 Evaluation of MSI Models

3.1 Canterbury Earthquake Liquefaction Case-History Dataset

The LPI , LPI_{ish} , LSN , and LSN_{ish} models were evaluated using 7167 Cone Penetration Test (CPT) liquefaction case histories from the M_w 7.1 September 2010 Darfield (2574 cases), the M_w 6.2 February 2011 Christchurch (2582 cases), and the M_w 5.7 February 2016 Valentine's Day (2011 cases) earthquakes in Canterbury, New Zealand, largely assembled by Maurer et al. [2–4, 13] and Geyin et al. [14]. Collectively these earthquake case histories are referred to as the Canterbury earthquakes (CE) case histories. The case histories consist of classifications of liquefaction manifestations, geotechnical and hydrological data, and ground-motion intensity measures. The severity of the liquefaction manifestations was based on post-event observations and high resolution aerial photographs and satellite imagery taken within a few days after the earthquakes. It should be noted that none of the MSI models being evaluated account for the influence of non-liquefiable, high fines content, high plasticity interbedded soil strata on the occurrence/severity of surficial liquefaction manifestations. Therefore, the MSI models can be best evaluated using case histories comprised predominantly clean to non-plastic silty sand profiles. Maurer et al. [3] found that sites in the region that have 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 to non-plastic silty sands. Accordingly, the 7167 liquefaction case histories used in this study only comprised CPT soundings that have $I_{c10} < 2.05$. Of the 7167 case histories, 38% of the case histories were categorized as “no manifestation” and the remaining 62% were categorized as either “marginal,” “moderate,” or “severe” manifestations following the Green et al. [15] classification.

3.2 Evaluation of Liquefaction Triggering and Severity of Surficial Liquefaction Manifestation

In evaluating the MSI models, FS is used as an input parameter. In the present study, FS was computed using the deterministic BI14 CPT-based liquefaction triggering model. Inherent to this process, soils with $I_c > 2.5$ were considered to be non-liquefiable [13]. Additionally, the FC required to compute q_{c1Ncs} was estimated using the Christchurch-specific $I_c - FC$ correlation proposed by Maurer et al. [13].

For each CE case history, the predictive efficacies of the LPI , LPI_{ish} , LSN , and LSN_{ish} models were compared by performing receiver operating characteristic (ROC) analyses on the CE dataset. In ROC analyses, the area under the ROC curve (AUC) can be used as a metric to evaluate the predictive performance of a diagnostic model (e.g., MSI model), where a higher AUC value indicates better predictive capabilities (e.g., [16]), e.g., a random guess returns an AUC of 0.5 and a perfect model returns an AUC of 1.

3.3 Results and Discussion

The results from ROC analyses show that the AUC values returned by the four different MSI models follow the order: $LPI \approx LPI_{ish} > LSN \approx LSN_{ish}$. As such, two main observations can be made. *First*, despite accounting for the limiting-crust-thickness phenomenon, LPI_{ish} and LSN_{ish} did not show improvements over LPI and LSN , respectively. This is likely due to the fact that the majority of case histories are located in eastern Christchurch where the groundwater table is shallow (usually ranging between ~ 1 – 2 m). As a result, the limiting-crust-thickness phenomenon may not have much of an influence on the severity of surficial liquefaction manifestations for the cases analyzed. *Second*, the higher AUC s for the LPI and LPI_{ish} models than for the LSN and LSN_{ish} models indicate that the latter group performs more poorly despite accounting for the influence of soil density on the occurrence/severity of surficial liquefaction manifestation via the FS - D_r - ε_v relationship, contrary to what would be expected. The most likely reason for the poorer performance of the LSN and LSN_{ish} models is that the influence of post-triggering volumetric strain potential of medium-dense to dense soils on the severity of surficial liquefaction manifestations is being double-counted by these models. This is because FS , which is used as an input to compute ε_v , inherently accounts for such effects via the shape of the cyclic resistance ratio curve ($CRR_{M7.5}$ curve).

Specifically, the $CRR_{M7.5}$ curves likely tend towards vertical at medium to high penetration resistance due to dilative tendencies of medium-dense to dense soils that inhibit the surficial liquefaction manifestation, even if liquefaction is triggered at depth. Accordingly, while the existing triggering curves are often thought of as “actual” or “true” triggering curves in current practice, in reality they are combined “triggering” and “manifestation” curves. This is mainly because the $CRR_{M7.5}$ curves are based on the liquefaction response of profiles inferred from post-earthquake surface observations at sites. Sites without surficial evidence of liquefaction are classified, by default, as “no liquefaction,” despite the possibility of liquefaction having been triggered at depth, but not manifesting at the ground surface. Consequently, inherent to the resulting triggering curve are factors that relate not only to triggering, but also to post-triggering surface manifestation.

4 Conclusions

- The predictive efficacies of the four MSI models were evaluated using 7167 well-documented CPT liquefaction case histories from the 2010–2011 Canterbury earthquake sequence and the 2016 Valentine’s Day earthquake; the case histories comprised predominantly clean to non-plastic silty sand profiles. These models were evaluated in conjunction with the deterministic BI14 triggering model to compute FS .
- The predictive efficacies of LSN_{ish} and LSN models were lower than those of LPI and LPI_{ish} , despite the former two MSI models accounting for the additional influence of soil density on the severity of surficial liquefaction manifestation via the $FS-D_r-\varepsilon_v$ relationship. The likely reason for this is that the influence of post-triggering volumetric strain potential on the severity of surficial liquefaction manifestation is being “double-counted” by the LSN and LSN_{ish} models, since the shape of the $CRR_{M7.5}$ curve inherently accounts for the dilative tendencies of medium-dense to dense soils, which inhibit surficial liquefaction manifestations even when liquefaction is triggered at depth.
- These findings suggest that current frameworks for predicting the occurrence/severity of surficial liquefaction manifestation do not account for the mechanics of triggering and manifestation in a proper and sufficient manner. While the triggering curves are assumed to be “true” (i.e., free of factors influencing manifestation), in reality they inherently account for some of the factors controlling surficial manifestation of liquefaction, particularly for denser soils. This implies that development of mechanistically more rigorous MSI models that are used in conjunction with simplified triggering models will not necessarily result in improved liquefaction damage potential predictions and may result in less accurate predictions.

Acknowledgements. This research was funded by National Science Foundation (NSF) grants CMMI-1751216, CMMI-1825189, and CMMI-1937984, as well as Pacific Earthquake Engineering Research Center (PEER) grant 1132-NCTRBM and U.S. Geological Survey (USGS) award G18AP-00006. This support is gratefully acknowledged, as well as access to the NZGD. However, any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of NSF, PEER, USGS, or the NZGD.

References

1. Iwasaki, T., Tatsuoka, F., Tokida, K., Yasuda, S.: A practical method for assessing soil liquefaction potential based on case studies at various sites in Japan. In: 2nd International Conference on Microzonation, 26 November–1 December, San Francisco, CA, USA, pp. 885–896 (1978)
2. Maurer, B.W., Green, R.A., Cubrinovski, M., Bradley, B.A.: Evaluation of the liquefaction potential index for assessing liquefaction hazard in Christchurch, New Zealand. *J. Geotech. Geoenviron. Eng.* **140**(7), 04014032 (2014)
3. Maurer, B.W., Green, R.A., Cubrinovski, M., Bradley, B.: Fines-content effects on liquefaction hazard evaluation for infrastructure during the 2010–2011 Canterbury, New Zealand earthquake sequence. *Soil Dyn. Earthq. Eng.* **76**, 58–68 (2015)

4. Maurer, B.W., Green, R.A., Cubrinovski, M., Bradley, B.: Assessment of CPT-based methods for liquefaction evaluation in a liquefaction potential index framework. *Géotechnique* **65**(5), 328–336 (2015)
5. Upadhyaya, S.: Development of an improved and internally-consistent framework for evaluating liquefaction damage potential. Doctoral dissertation, Virginia Tech, Blacksburg, VA (2019)
6. Maurer, B.W., Green, R.A., Taylor, O.S.: Moving towards an improved index for assessing liquefaction hazard: lessons from historical data. *Soils Found.* **55**(4), 778–787 (2015)
7. van Ballegooy, S., et al.: Assessment of liquefaction-induced land damage for residential Christchurch. *Earthq. Spectra* **30**(1), 31–55 (2014)
8. Ishihara, K.: Stability of natural deposits during earthquakes. In: 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, CA, USA, vol. 1, pp. 321–376 (1985)
9. Ishihara, K., Yoshimine, M.: Evaluation of settlements in sand deposits following liquefaction during earthquakes. *Soils Found.* **32**(1), 173–188 (1992)
10. Upadhyaya, S., Green, R.A., Maurer, B.W., Rodriguez-Marek, A., van Ballegooy, S.: Limitations of surface liquefaction manifestation severity index models used in conjunction with simplified stress-based triggering models. *J. Geotech. Geoenviron. Eng.* **148**(3), 04021194 (2022)
11. van Ballegooy, S., Green, R.A., Lees, J., Wentz, F., Maurer, B.W.: Assessment of various CPT based liquefaction severity index frameworks relative to the Ishihara (1985) H_1 - H_2 boundary curves. *Soil Dyn. Earthq. Eng.* **79**(Part B), 347–364 (2015)
12. Zhang, G., Robertson, P.K., Brachman, R.W.I.: Estimating liquefaction-induced ground settlements from CPT for level ground. *Can. Geotech. J.* **39**(5), 1168–1180 (2002)
13. Maurer, B.W., Green, R.A., van Ballegooy, S., Wotherspoon, L.: Development of region-specific soil behavior type index correlations for evaluating liquefaction hazard in Christchurch, New Zealand. *Soil Dyn. Earthq. Eng.* **117**, 96–105 (2019)
14. Geyin, M., Maurer, B.W., Bradley, B.A., Green, R.A., van Ballegooy, S.: CPT-based liquefaction case histories compiled from three earthquakes in Canterbury, New Zealand. *Earthq. Spectra* (2021) <https://doi.org/10.1177/8755293021996367>
15. Green, R.A., et al.: Select liquefaction case histories from the 2010–2011 Canterbury earthquake sequence. *Earthq. Spectra* **30**(1), 131–153 (2014)
16. Fawcett, T.: An introduction to ROC analysis. *Pattern Recogn. Lett.* **27**(8), 861–874 (2005)