Soil Dynamics and Earthquake Engineering 79 (2015) 335–346

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Assessment of liquefaction evaluation procedures and severity index frameworks at Christchurch strong motion stations

Liam M. Wotherspoon [a,*], Rolando P. Orense [a], Russell A. Green [b], Brendon A. Bradley [c], Brady R. Cox [d], Clinton M. Wood [e]

[a] Department of Civil & Environmental Engineering, University of Auckland, New Zealand
[b] Department of Civil & Environmental Engineering, Virginia Tech, Blacksburg, VA 24061, United States
[c] Department of Civil & Natural Resources Engineering, University of Canterbury, New Zealand
[d] Department of Civil, Architectural & Environmental Engineering, The University of Texas, Austin, TX 78712, United States
[e] Department of Civil Engineering, University of Arkansas, Fayetteville, AR 72701, United States

ARTICLE INFO

Article history:
Received 6 July 2014
Received in revised form
11 February 2015
Accepted 28 March 2015
Available online 23 April 2015

Keywords:
Liquefaction
Canterbury earthquake sequence
CPT
Strong motion stations

ABSTRACT

The objective of the study presented herein is to assess three commonly used CPT-based liquefaction evaluation procedures and three liquefaction severity index frameworks using data from the 2010–2011 Canterbury earthquake sequence. Specifically, post-event field observations, ground motion recordings, and results from a recently completed extensive geotechnical site investigation programme at selected strong motion stations (SMSs) in the city of Christchurch and surrounding towns are used herein. Unlike similar studies that used data from free-field sites, accelerogram characteristics at the SMS locations can be used to assess the performance of liquefaction evaluation procedures prior to their use in the computation of surficial manifestation severity indices. Results from this study indicate that for cases with evidence of liquefaction triggering in the accelerograms, the majority of liquefaction evaluation procedures yielded correct predictions, regardless of whether surficial manifestation of liquefaction was evident or not. For cases with no evidence of liquefaction in the accelerograms (and no observed surficial evidence of liquefaction triggering), the majority of liquefaction evaluation procedures predicted liquefaction was triggered. When all cases are used to assess the performance of liquefaction severity index frameworks, a poor correlation is shown between the observed severity of liquefaction surface manifestation and the calculated severity indices. However, only using those cases where the liquefaction evaluation procedures yielded correct predictions, there is an improvement in the correlation, with the Liquefaction Severity Number (LSN) being the best performing of the frameworks investigated herein. However scatter in the relationship between the observed and calculated surficial manifestation still remains for all liquefaction severity index frameworks.

1. Introduction

The city of Christchurch and some surrounding towns experienced widespread damage due to seismically induced liquefaction during the 2010–2011 Canterbury Earthquake Sequence (CES), beginning in 4 September 2010 with the M_w7.1 Darfield earthquake. Other notable earthquakes in this sequence were the 22 February 2011 M_w6.2 Christchurch earthquake, and the 13 June 2011 and 23 December 2011 events. Each resulted in widespread liquefaction, with the most severe damage occurring during the Christchurch earthquake [9,10].

Prior to the CES, assessments had shown that there was a high potential for liquefaction across most of the city [1,11]. This work used the simplified liquefaction evaluation procedures, first proposed by Seed and Idriss [30] and Whitman [37]. This procedure is largely based on empirical observations of laboratory and field data and has been continually refined as a result of newer studies and the increase in the number of field case histories (e.g., [41], [16]). Although the early versions of this procedure only proposed correlations relating standard penetration test (SPT) blow count to liquefaction resistance, subsequent studies have also proposed correlations that are based on cone penetration test (CPT) results (e.g., [28], [24], [16]). In developing these correlations, the field case histories were categorised as "liquefaction" and "no liquefaction," almost exclusively based on

* Correspondence to: Department of Civil & Environmental Engineering, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand. Tel: +64 9 3737599.
E-mail address: l.wotherspoon@auckland.ac.nz (L.M. Wotherspoon).

http://dx.doi.org/10.1016/j.soildyn.2015.03.022
0267-7261/

surficial evidence of liquefaction or the lack thereof. Surficial evidence of liquefaction includes the presence of sand ejecta, ground cracking and fissures, and lateral spreading at the ground surface in close vicinity to site investigation locations. The proposed boundaries separating the liquefaction and no liquefaction cases were often conservatively defined, providing a lower bound for the estimated liquefaction resistance [41]. This paper focusses on CPT-based simplified liquefaction evaluation procedures proposed by Robertson and Wride [28], Moss et al. [24], and Idriss and Boulanger [16].

The simplified procedures indicate whether or not liquefaction is predicted to occur at a given depth in the soil profile, but it does not provide an indication of the cumulative effect of liquefaction triggering throughout the soil column and the severity of manifestation at the ground surface. Results from the simplified procedures can be used as inputs in liquefaction severity index frameworks to predict the severity of surficial liquefaction manifestation. One of the earliest proposed and most widely used liquefaction severity index frameworks is the Liquefaction Potential Index (LPI) proposed by Iwasaki et al. [18], equal to:

$$\mathrm{LPI} = \int_0^{20\ \mathrm{m}} F_1 W(z) dz$$

where $F_1 = 1 - \mathrm{FOS}$ for $\mathrm{FOS} \leq 1.0$, and $F_1 = 0$ for $\mathrm{FOS} > 1.0$. $W(z) = 10 - 0.5z$, where FOS is the factor of safety against liquefaction and z is depth in metres. Computed LPI values were correlated to severity of surficial liquefaction manifestations using a borehole database and observations from Japanese earthquakes, where the FOS were computed using the SPT-based liquefaction evaluation procedure specified in the Japanese Specifications for Highway Bridges [19]. Using this approach liquefaction severity was defined as: minor for $0 < \mathrm{LPI} \leq 5$, moderate for $5 < \mathrm{LPI} \leq 15$, and major for $\mathrm{LPI} > 15$. A number of studies have presented modified versions of these classifications (e.g. [31,26]). Work by Toprak and Holzer [33] following the 1989 Loma Prieta earthquake suggested that there is unlikely to be any surface manifestations for an LPI less than 5. Using a database from Taiwan and the Robertson and Wride [28] CPT-based liquefaction evaluation procedure, Lee et al. [22] showed that the surface manifestation severity is low if $\mathrm{LPI} < 13$, and extremely high if $\mathrm{LPI} > 21$. Maurer et al. [23] analysed a database of almost 1200 CPT soundings from Christchurch using the Robertson and Wride [28] procedure, finding that the original LPI framework was generally able to predict moderate–severe surficial manifestation severity, but less able to predict cases with lesser severity.

The magnitude of post-liquefaction consolidation settlement (S) has also been proposed as a proxy for the severity of surficial liquefaction manifestation. Zhang et al. [42] proposed the following relation for computing S:

$$S = \sum_{i=1}^{j} \varepsilon_{vi} \Delta z_i$$

where ε_v is the volumetric strain due to post-liquefaction consolidation of soil layer i,Δz_i is the thickness of layer i, and j is the number of soil layers. The Zhang et al. model has been modified by Juang et al. [20] to account for the likelihood of liquefaction in each soil layer.

A recently proposed liquefaction severity index framework is the Liquefaction Severity Number (LSN) [35]. The LSN was developed using the database of approximately 5500 CPTs across the city of Christchurch and observations of severity of surficial liquefaction manifestations in residential areas following the Darfield, Christchurch, and 13 June 2011 earthquakes. The LSN is defined as:

$$\mathrm{LSN} = 1000 \int_0^{10\ \mathrm{m}} \frac{\varepsilon_v}{z} dz$$

where ε_v is defined as above and is a function of FOS. FOS used in the development of the LSN was computed using the Idriss and Boulanger [16] CPT-based liquefaction evaluation procedure, and the volumetric strains were computed using Zhang et al. [42]. LSN is calculated using the top 10 m of the soil profile only. Using this approach liquefaction severity was defined as: minor for $0 < \mathrm{LSN} \leq 20$, moderate for $20 < \mathrm{LSN} \leq 50$, and major for $\mathrm{LSN} > 50$. From the analysis of the Christchurch dataset, the LSN showed a better correlation with the observed severity of surficial manifestations than LPI and post-liquefaction consolidation settlement.

Prior to the start of the CES, the city and surrounding towns had a large network of strong motion stations (SMSs) installed, which recorded a vast database of strong ground motions [2,3,13]. This paper focuses on the SMSs installed prior to the Darfield earthquake, with the locations of the SMS study sites in Christchurch presented in Fig. 1. Apart from one location (Hulverstone Drive Pumping Station, HPSC), all SMS locations are outside the red zone regions of Christchurch and Kaiapoi that suffered the most severe land damage due to soil liquefaction [29].

The study presented herein assesses three commonly used CPT-based liquefaction evaluation procedures (i.e., [28,24,16]) and three liquefaction severity index frameworks (i.e., LPI, post-liquefaction consolidation settlement, and LSN) using data from the 2010–2011 Canterbury earthquake sequence. Specifically, post-event field observations, ground motion recordings, and results from a recently completed extensive geotechnical site investigation programme at selected strong motion stations (SMSs) in the city of Christchurch and surrounding towns are used herein. Unlike similar studies that used data from free-field sites, accelerogram characteristics at the SMS locations are used to assess the performance of liquefaction evaluation procedures prior to their use in the computation of surficial manifestation severity indices. This allows the exclusion of erroneously predicted liquefaction triggering cases from being used in the assessment of the liquefaction severity index frameworks.

2. Regional geology and geotechnical data

The city of Christchurch is located on the east coast of the South Island of New Zealand, on the edge of the Canterbury Plains, a large area (approximately 160 km long and up to 60 km wide) formed by the overlapping alluvial fans of glacier-fed rivers. The surface geology within the city consists primarily of the Springston Formation (holocene alluvial gravels, sands and silts) and the Christchurch Formation (dune and beach sands) [4].

The SMSs within Christchurch and the near surface stratigraphy, as outlined in Brown and Weeber [4], is presented in Fig. 1. In this figure, the locations of different soil deposits and shallow gravel layers are presented. The sub-surface geology profiles for the SMSs vary significantly across the city, with gravel layers dominating the stratigraphy in the west of the city, while in the east there are no contiguous shallow gravel layers present. Hulverstone Drive Pumping Station (HPSC), New Brighton Library (NBLC), and North New Brighton School (NNBS) are located on the Christchurch Formation (the yellow zone in Fig. 1). Heathcote Valley Primary School (HVSC) is situated on loess and volcanic colluvium deposits of the Banks Peninsula loess formation. Outside of the range of Fig. 1, the Lyttelton Port (LPCC) SMS is founded on basalt that is part of the Lyttelton Group Volcanics. The remainder of the SMSs are located on the Springston Formation (including Kaiapoi North School (KPOC)).

2.1. Site specific geotechnical investigation

Prior to 2010, little information regarding the subsurface geotechnical characteristics of the SMS sites in and around Christchurch was available. As noted by Cousins and McVerry [8], the soil profiles and