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Validation of three liquefaction assessment software packages with CPT data from the New Zealand geotechnical database

M. Daví & I.J. Tromans
Jacobs, London, UK

B. Carvalho
EDP Renewables, Porto, Portugal

A.T. Gomes
University of Porto, Porto, Portugal

ABSTRACT: An in-house soil liquefaction assessment tool using a CPT-based simplified procedure has been developed using MathCad in order to investigate the capabilities and limitations of three commercially available software packages, namely CLiq, LiquefyPro and Settle3D. The validation is carried out using three high quality CPT measurements from the New Zealand Geotechnical Database, selected as to include locations characterized by none, minor and major liquefaction, based on post-earthquake observations. The performance of each software package is assessed by comparing results in terms of factor of safety against liquefaction and estimating liquefaction-induced settlements. The benchmarking exercise against well-documented case histories of liquefaction helped to identify inherent differences among the software packages and the effect of those in the assessment of liquefaction and the estimation of liquefaction-induced settlements. The study highlighted the benefits of having a custom-made in-house tool to assess soil liquefaction, flexible to adaptation and updates as new techniques become available.

1 INTRODUCTION

The evaluation of earthquake-induced liquefaction and its consequences is a very active field within the earthquake engineering community. Since 1971, simplified procedures have evolved as a standard of practice for the evaluation of the liquefaction resistance of soils. A number of approaches have been proposed over the years by various authors, based on the evaluation of the soil resistance from field measurements derived from standard penetration testing (SPT), cone penetration testing (CPT), the Becker penetration test (BPT) or shear wave velocity (V_s). The basic framework of these simplified methods is based on the evaluation of the Factor of Safety (FS) against liquefaction as the ratio between the cyclic stress ratio (CSR), measuring the earthquake loading, and the cyclic resistance ratio (CRR), measuring the soil resistance. A thorough review of the available methods in the literature was the topic of discussion of the 1996 and 1998 National Science Foundation/National Centre for Earthquake Engineering Research (NFS/NCEER) workshops (Youd et al. (2001)), and more recently by the work published by the National Academies of Science, Engineering and Medicine (NASEM, 2016), reporting key findings and recommendations on the state of the art and practice in the assessment of earthquake-induced soil liquefaction and its consequences.

Within such an active field, a number of commercial software packages have been developed over the years, to assist practitioners in the implementation of various published procedures for the assessment of liquefaction and estimation of induced settlements. However, the commercially available software can have particular limitations whether due to a lack of transparency in the way that they implement one or more assessment methodologies, limited flexibility or because they use superseded techniques. The aim of this paper was to review the capabilities and limitations of three commercial software packages, namely CLiq (Geologismiki), LiquefyPro (CivilTech) and Settle3D (Rocscience). The validation was carried out testing the three software packages against well-documented case histories using a common empirical liquefaction evaluation method. All three sets of results were compared against each other and, based on the findings, an in-house tool was developed in Mathcad to further test the performance of the software, offering more transparency and greater control over the input and output of the analysis.

2 LIQUEFACTION AND SETTLEMENTS ASSESSMENT METHOD

The empirical CPT-based method of Robertson & Wride (1998) (R&W98) was selected to assess the performance of the software, as it is one of the most well-established methods in use in the earthquake engineering community and implemented in all three software packages. The use of CPT data in preference to SPT or V_s data is considered best practice for in situ field-estimates of liquefaction (NASEM, 2016). CPTs have the advantage of offering greater continuity and repeatability of data compared to SPTs, are less dependent on the equipment operator, can be performed with relative speed and economy and are able to detect thin layers of liquefiable strata and, moreover, can be coupled with measurements of V_s. by means of an integral seismic CPT module.

The R&W98 method expresses the CRR based on the equivalent clean sand normalised CPT penetration resistance (q_c), corrected for overburden stress and the grain characteristic correction factor of the soil (K_c), as a function of the soil behaviour index (I_c). The procedure requires the application of adjustment factors, such as on the overburden stress (C_Q), the magnitude scaling factor (MSF) and stress reduction factor (r_d), which should be applied consistent with the way the liquefaction method was originally developed.

Volume loss due to the dissipation of excess pore pressure in the liquefied soil during and after an earthquake generally results in ground surface settlements. In the literature there are various procedures for the estimation of the settlements in dry and saturated soil. Within the scope of this study, the methods proposed by Tokimatsu & Seed (1987) (T&S87) and Zhang et al. (2002) (ZETAL02) are used for the evaluation of the saturated soil settlements, as those are the ones implemented in the software packages. For the dry soil settlements, the methods proposed by Tokimatsu & Seed (1987), Ishihara & Yoshimine (1992) (I&Y92) and Robertson & Shao (2010) (R&S10) are implemented.

3 CASE HISTORY SELECTION

In order to assess the performance of the different commercial software packages, it was important to use well-documented case histories of observed liquefaction with high quality CPT data. For this purpose, data were selected from the New Zealand Geotechnical Database (NZGD), one of the most internationally recognized high quality and publicly accessible sources of geotechnical data, also recommended by the NASEM (2016) for the purposes of validation of liquefaction analysis. The NZGD was created to provide and promote exchange of geotechnical data collected after the 2010-2011 Canterbury earthquake sequence in New Zealand, which triggered widespread cases of liquefaction in the region. The NZGD includes more than 22,000 CPT profiles and more than 10,000 borehole logs from well-characterised sites throughout the Canterbury region. In addition to this, it includes aerial photographs, field observations, LiDAR (Light Detection and Ranging) data and provides interpretation maps of vertical ground movement and liquefaction severity from observations. Following the approach by Tonkin & Taylor (2013), the liquefaction severity is classified as: “no liquefaction”, “minor liquefaction” and “moderate-to-severe liquefaction”.

Three different case histories were selected to validate the three software packages and data were selected according to the following criteria: i) the use of CPT data, as generally considered the preferred method for field based estimates of liquefaction resistance, ii) the use of high quality data, penetrating the depths of interest, ideally close to strong-motion stations, for a more reliable characterisation of the peak ground acceleration (PGA), iii) the availability of reliable pre- and post-groundwater levels from nearby wells, iv) the availability of detailed soil profiles from nearby boreholes to improve the interpretation of the CPTs and v) the availability of a liquefaction severity classification based on the observations.

It was decided to use as a benchmark for the software validation three case histories, one for each level of liquefaction severity. The screening process of the case histories benefitted from the work carried out by Green et al. (2014), which included processing and assessment of a number of high quality CPT profiles in the region. Based on the previously listed criteria, the following three CPT profiles were selected: CPT-KAS-19, CPT-KAN-26, CPT-NBT-03. Two of those (CPT-KAN 26 and CPT-NBT-03) were also assessed in the Green et al. (2014) study. Those CPT profiles were used to estimate the liquefaction triggered by the 22nd of February 2017, magnitude M 6.2 Christchurch earthquake, which caused widespread liquefaction in the Central Business District of Canterbury (Cubrinovski et al. (2011)). A summary of the main parameters of interest, including PGA from the closest strong-motion stations for each of the selected CPTs is presented in Table 1.

The location of the selected three CPTs is shown in Figure 1, super-imposed on a map showing the liquefaction severity zones from the interpretation of aerial photography, as provided by the NZGD. CPT-KAS-19 is located in a zone of no observed liquefaction, CPT-KAN-26 in a zone of minor liquefaction and CPT-NBT-03 in a zone with moderate-to-severe liquefaction, as also summarised in Table 1. The estimates of total settlements provided by the NZGD on the basis of the interpretation of aerial photography are indicated in Table 1.

Table 1. Summary of the liquefaction case histories used as benchmarking for the validation of the three software packages.

CPT test cases	CPT-KAS-19	CPT-KAN-26	CPT-NBT-03
Test Date	11/11/2010	15/11/2010	28/01/2011
Earthquake event	22/02/2011 M 6.2	22/02/2011 M 6.2	22/02/2011 M 6.2
Water level during CPT (m)	2.0	1.50	2.4
Water level during earthquake (m)	0.94	0.50	1.18
PGA (g)	0.21	0.18	0.34
Distance to strong motion station (m)	1,350	720	360
Closest borehole	BH1_4902	BH_21844	BH_1829
Distance to borehole (m)	63.10	199.50	86.40
Liquefaction severity	none	minor	moderate-severe
Total Settlement (cm)	0-10	0-10	10-20

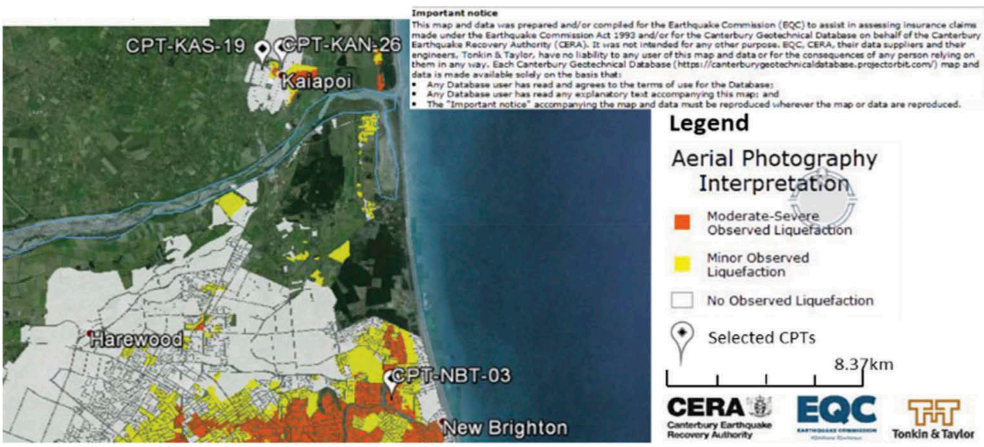

Figure 1. Locations of the three selected CPTs: CPT-KAS-19, CPT-KAN-26, CPT-NBT-03 overlain onto the liquefaction severity map (NZGD).

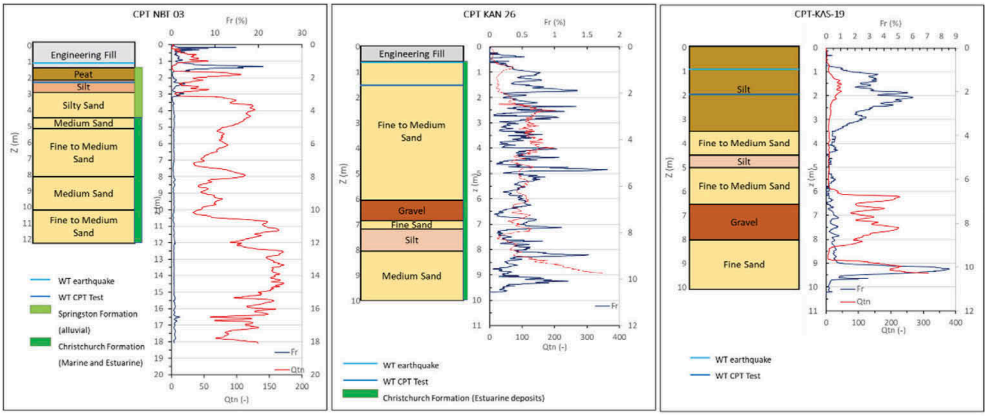

Figure 2. Soil profile and graphs of the cone penetration resistance (Q_{tn}) and friction ratio (F_r) for each of the three selected CPTs profiles: CPT-NBT-03, CPT-KAN-26 and CPT-KAS-19.

The soil profiles for each of the three CPTs were developed by making use of the available geology information (Browne et al. (2012), Taylor et al. (2012)) and by interpreting the CPT profiles with the stratigraphy information derived from nearby boreholes (as indicated in Table 1). The soil profiles together with the cone penetration (Q_{tn}) and friction ratio (F_r) profiles for each of the three CPTs are shown in Figure 2.

4 COMMERCIAL SOFTWARE PACKAGES

CLiq (version 1.7) is a CPT-based soil liquefaction software, developed by GeoLogismiki in collaboration with Gregg Drilling Inc. and Professor Peter Robertson. The software is mainly focused on CPT-based assessment, but it also includes options for SPT or Vs-based liquefaction analysis. CLiq allows the user to define two groundwater levels, for during the earthquake and during the CPT test, used for the calculation of the CRR and CSR respectively and

Table 2. Summary of the methods built-in in the three software packages adopted, using CPT data.

Parameters	CLiq	LiquefyPro	Settle3D
CSR	Seed Idriss (1971)	Seed Idriss (1971)	Seed Idriss (1971), Idriss (1999), Kayen (1999), Cetin et al. (2004), Liao & Whitman (1986)
CRR	R&W98, Robertson (2009), Moss et al. (2009), Idriss & Boulanger (2008), Boulanger & Idriss (2014)	Seed & De Alba (1986), Suzuki et al. 1997, Robertson & Wride (1997), R&W98	Robertson & Wride (1997), R&W98, Boulanger & Idriss (2004), Moss et al. (2006)
MSF	Youd et al. (2001), Moss et al. 2006, Idriss & Boulanger (2008)	Youd et al. (2001)	Idriss (1999), Andrus & Stokoe (1997), Idriss & Boulanger (2008), Youd & Noble (1997), Cetin et al. (2012), T&S87
r_d	Blake (1996)	Youd et al. (2001)	Youd et al. (2001)
Dry soil settlements	R&S10	T&S87	N/A for CPT data
Saturated soil settlements	ZETAL02, Idriss & Boulanger (2008)	T&S87, I&Y92	N/A for CPT data

to allow definition of unit weights for each layer. The software allows a high level of user control for example in the definition of the I_c threshold value, or the limitation for the overburden stress correction factor, C_N. For the evaluation of CSR, CRR, MSF, r_d and the evaluation of the dry and saturated soil settlements, it offers the options summarised in Table 2. CLiq provides in both tabular and graphical formats all the intermediate steps of the procedure followed; this high level of transparency greatly assisted the validation process.

LiquefyPro (version 5.1) is a software developed by CivilTech Software, designed to evaluate liquefaction potential and estimate settlement of soils due to seismic loads. The software offers the user the option of choosing among different methods to carry out the liquefaction assessments based on SPT, BPT or CPT data. For CPT data, it implements the methods presented in Table 2. As for CLiq, it includes the option of separately defining the water table values measured during the CPT test and during the earthquake. Another interesting feature is the option given to the user to either define the fines content or estimating it from CPT data (using the R&W98 method). In terms of output provided by the software, it returns a complete log providing intermediate parameters.

Settle3D (version 3.17) is a 3-dimensional geotechnical analysis software developed by Rocscience to perform analysis of vertical consolidation and settlements, with the added functionality of liquefaction analyses. The software implements different methods based on CPT, SPT or Vs data. Using CPT data, the methods implemented in the software are summarised in Table 2. Settle3D does not provide settlement estimation if CPT data are used. In terms of output provided by the software, depth profiles of the CSR, CRR and FS are provided, but the software does not provide the user with any intermediate parameters.

5 VALIDATION APPROACH AND DISCUSSION OF THE RESULTS

The performance of each software package with respect to liquefaction assessment was reviewed by comparing all three sets of outputs in terms of FS adopting the R&W98 empirical procedure. With regard to settlement estimation, this was assessed using the predictive methods for dry and saturated soil incorporated within each software package. As Settle3D did not provide direct settlement estimation from CPT data it was not included in this comparison. The methods selected for the evaluation of the CSR, CRR, MSF and r_d for the liquefaction assessment and for the settlement evaluation for the validation of the three software packages are presented in Table 3.

As part of the validation exercise, some limitations were noted in the modelling capabilities of the software LiquefyPro and Settle3D, while no particular limitations were found in CLiq. Among the limitations that were found in LiquefyPro were a fixed maximum number of CPT data points (1,200), requiring the user to resample the data as this limit gets exceeded; the missing application of the threshold value of 1.7 to C_N values, as recommended by Youd et al. (2001). The validation also showed that it did not apply the correction K_c =1 for values of $1.64 < I_c < 2.36$ and F <0.5% as suggested by R&W98 to distinguish a loose clean sand from a sand containing fines.

With regards to Settle3D, the main limitation was the general "opacity" in the presentation of the calculation results which made the validation process difficult; the definition of only one water level, instead of two distinct values for the correct evaluation of the CSR and CRR. As the software did not implement the Youd et al. 2001 method for the evaluation of the

Table 3. Summary of the methods selected for the validation of the three software packages.

Parameters	CLiq	LiquefyPro	Settle3D
CSR	Seed Idriss (1971)	Seed&Idriss (1971)	Seed&Idriss (1971)
CRR	R&W98	R&W98	R&W98
MSF	Youd et al. 2001	Youd et al. 2001	Andrus&Stokoe (1997)
r_d	Blake (1996)	Liao&Whitman (1986)	Liao&Whitman (1986)
Dry soil settlements	R&S10	T&S87; I& 92	N/A
Sat. soil settlements	ZETAL02	T&S87	N/A

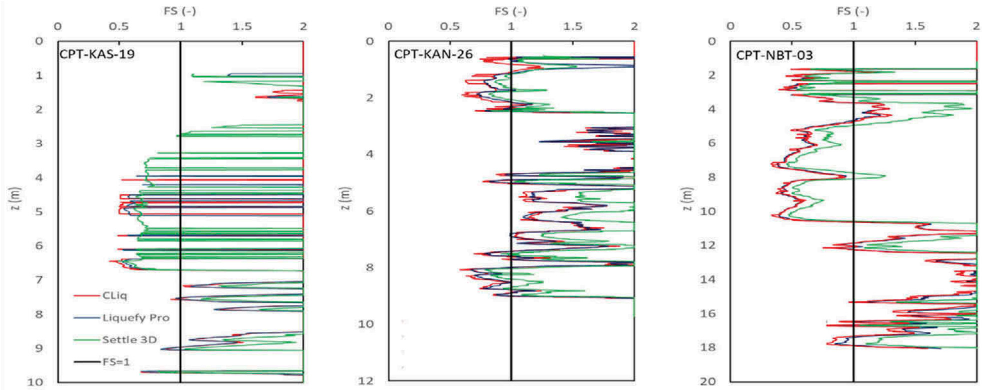

Figure 3. Comparison of the factor of safety (FS) obtained from the three software CLiq, LiquefyPro and Settle3D for the three CPT profiles: CPT-KAS-19, CPT-KAN-26, CPT-NBT-03.

MSF, the expression provided by Idriss (1999) was used as the one providing most similar values. It was found that the software did not implement the automatic fines correction procedure on the cone penetration values as required by the R&W98 method, so that the user had to manipulate the input parameter to get the same correction.

The comparison among the software outputs is shown in terms of FS profiles against depth for the three CPTs in Figure 3. Results indicate that while LiquefyPro and CLiq presented a similar output, with comparable thicknesses and depths of the liquefiable layers, Settle3D was found to give consistently higher FS for all three case histories. A more detailed analysis of the intermediate parameters (e.g. I_c) revealed that the differences noticed between LiquefyPro and Cliq were because LiquefyPro did not implement the threshold of 1.7 on C_N, which especially affected results at shallow depths; the adoption in the software of different expressions for r_d or MSF was found to have a very marginal effect on the results. By analysing the output from Settle3D, it was found that it consistently gave larger estimates of the soil resistance CRR for the case histories examined, compared to the other two software products, which in turn led to a higher FS; this was difficult to explain due to the limited transparency offered by the software.

In terms of liquefaction-induced settlements, only the results obtained by CLiq and LiquefyPro were available. For the saturated soil component, the validation showed that the differences in the prediction of the software packages were basically due to the different evaluation procedures implemented in the software, although results were overall in reasonable agreement. The method by I&Y92 implemented in LiquefyPro produced results more similar to

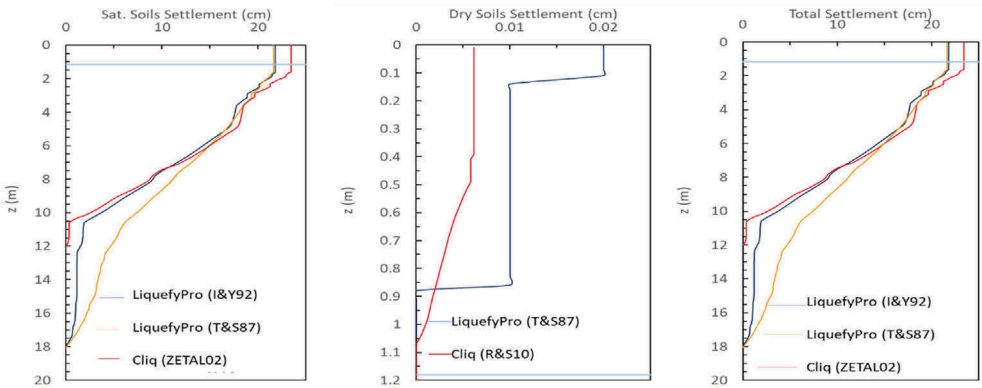

Figure 4. Comparison in terms of total, dry and saturated settlements as obtained from Cliq and LiquefyPro for one representative case history: CPT-NBT-03.

those from the ZETAL02 method adopted in CLiq, than the alternative option by T&S87. This result was expected as ZETAL02 is based on the I&Y92 approach. By analysing the dry soil settlement curves, it was found that the differences in the prediction of the software packages were mainly due to the inherent difference in the evaluation procedures implemented. The method by T&S87 implemented in LiquefyPro produced greater settlements than the R&S10 method adopted in CLiq. However, these divergences had very little influence on the final cumulative settlements owing to the overriding effect of the settlements from below the water table. The comparison is shown in Figure 4, for only one of the three case histories: CPT-NBT-03, with a total settlement ranging between 23 and 24.5cm, in relatively good agreement with the post-earthquake information provided by NZDB (10-20cm). Total settlements ranged between 8 to 11 cm and 4 to 5 cm for CPT-KAN-26 and CPT-KAS-19, confirming the good agreement with NZGD interpretation (0-10cm).

Based on the findings of the study, CLiq was identified as the software package with the greatest flexibility and transparency of outputs. For the assessment of liquefaction based on the CPT R&W98 method, CLiq and LiquefyPro gave very similar results for all three examined case histories whilst Settle3D gave consistently higher FS.

5.1 *Comparison with in-house Mathcad tool*

The second step in the validation procedure consisted in checking the results with an independent in-house tool developed in Mathcad, the engineering calculation software by PTC. Thanks to the flexibility provided by the tool, it was possible to implement some of the modifications to the original R&W98 method recommended in Robertson & Cabal (2015) and Robertson (2009) which were considered valuable to the study. The modifications introduced are summarised here: i) for the calculation of the CRR the set of equations proposed by Robertson (2009) were implemented, ii) for the evaluation of the MSF, the method recommended by Youd et al 2001 was implemented, iii) for the evaluation of the saturated soil settlements induced by liquefaction, the method developed by ZETAL02 was implemented, while for the dry soil settlements the CPT-based procedure proposed by R&S10 was implemented. As all of the above-mentioned modifications to the R&W98 approach were also implemented in CLiq, it was decided to only test this software in the second part of the validation. As part of the procedure, the evaluation of the Liquefaction Potential Index (LPI) by the method of Iwasaki et al. 1978 and Luna & Frost (1998) was also implemented in Mathcad in order to compare the prediction with the liquefaction severity classification provided in the NZGD. This resulted in LPI = 22 (“severe”), 6 (“moderate”), 4 (“minor”) for CPT-NBT-03, CPT-KAN-26 and CPT-KAS-19 respectively. Although on the conservative side, the LPIs were found in reasonably good agreement with the liquefaction severity classes in Table 1.

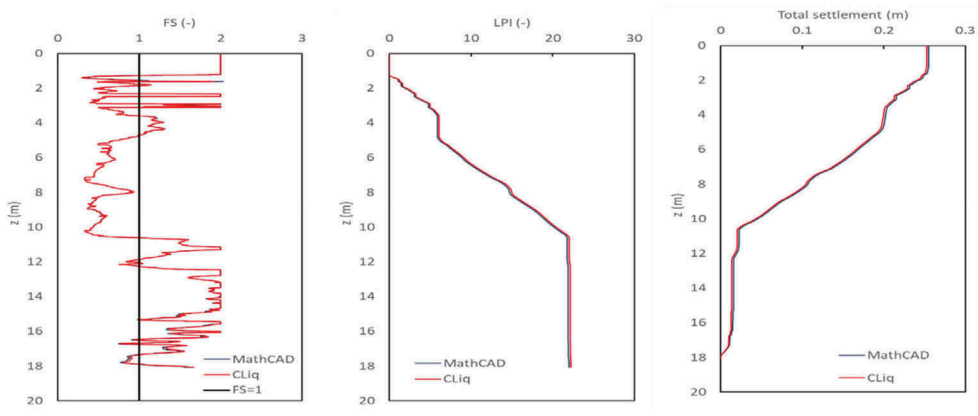

Figure 5. Comparison of Mathcad and Cliq in terms of FS, LPI & total settlement for CPT-NBT-03.

Only the results for the worst case of liquefaction (CPT-NBT-03) are presented in terms of FS and total settlements, indicating an excellent agreement (Figure 5).

6 CONCLUSIONS

Three software packages commonly used in engineering practice, namely CLiq (version 1.7), LiquefyPro (version 5.1) and Settle3D (version 3.17) were validated by means of the CPT-based R&W98 liquefaction assessment method, using high-quality CPT data from the extensive NZGD archive. Liquefaction observations from the 22/02/2011 M6.2 Christchurch earthquake were used to validate the empirical liquefaction assessment. The capabilities and limitations of each software were discussed. Through the validation exercise it was possible to explore the limitations and capabilities of the three software packages. It was concluded that for the software versions available at the time of the assessment, CLiq provided the greatest flexibility and transparency, incorporating the most recent methodological updates available from the published literature. CLiq and LiquefyPro gave very similar results for the examined case histories, whether for FS evaluation or liquefaction-induced settlement estimation whilst Settle3D consistently gave higher FS for the examined cases. The development of an in-house tool in Mathcad provided a means of independent validation of the commercial software packages and offered greater control over the implementation of the desired liquefaction method and greater transparency and flexibility for future adaptation. It is noted that the comparisons presented herein only strictly relate to the software versions used at the time. Subsequent updates (CLiq v.3.0, LiquefyPro v.5.8 and Settle3D v.4.0) may have addressed limitations identified in the current study.

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