Mitigation of damages to residential buildings caused by liquefaction-induced settlement

Atténuation des dégats causés par ruissellement induit par liquéfaction des sols pour des immeubles résidentiels

Zhiyuan Zhang, Rolando P Orense
Department of Civil & Environmental Engineering, University of Auckland, New Zealand, r.orense@auckland.ac.nz

ABSTRACT: Following the Christchurch earthquake sequence, many residential houses settled and tilted as a result of widespread liquefaction within the affected region. To investigate the depth of ground improvement required to meet the requirements for acceptable house settlement, numerical analyses were conducted using the software FLAC. Firstly, verification exercises were carried out at sites where considerable damage has occurred to validate the numerical models used. Next, considering a representative site, a typical house was modeled and various parameters, including width and stiffness of ground improvement, input motion and liquefiable layer thickness, were considered to assess their effects on the required improvement depth. Results show that the improvement width did not influence the required depth, as long as it extends outside the foundation perimeter by more than 1m. The stiffness of the improved ground did not have any significant effect, provided it is sufficiently stiff not to liquefy. Different input motions produced different required depths, while an increase in liquefiable layer thickness resulted in thicker depth until a limiting value was reached. The results showed reasonable agreement with the Ishihara's chart.

RÉSUMÉ : Suite à l'épisode de séisme intervenu à Christchurch, plusieurs bâtiments résidentiels se sont enfoncées et inclinés suite à la vaste liquéfaction du sol sur le territoire affecté. Afin d'évaluer la profondeur d'amélioration des sols suffisante au respect des critères de déplacement acceptables, des analyses numériques sont menées à l'aide du logiciel FLAC. Dans un premier temps, des exercices d'étalonnage ont été conduits sur des sites ayant subi d'importants dégâts dans le but de valider les modèles numériques. Par la suite, un profil de maison standard a été modelisé en se basant sur un terrain représentatif et l'influence de différents paramètres, dont la largeur et la rigidité du sol amélioré, le mouvement d'entrée et l'épaisseur de la couche liquéfiable, a été évaluée. Les résultats indiquent que la largeur n'a aucune influence sur la profondeur requise tant qu'elle dépasse le périmètre de fondation d'au moins 1m. L'amélioration de la rigidité du sol, quant à elle, n'offre pas de changements significatifs à condition d'avoir un sol suffisamment dur pour ne pas liquéfier. Différents mouvements d'entrée aboutissent à des profondeurs requises différentes, tandis qu'une épaisseur de couche de liquéfaction plus élevée accroît la profondeur jusqu'à atteindre une valeur limite. Les résultats sont raisonnablement en accord avec le graphique d'Ishihara.

KEYWORDS: earthquake; liquefaction; building settlement; ground improvement; mitigation

1 INTRODUCTION

The shaking from the 2010-2011 Christchurch Earthquake sequence (CES) induced liquefaction of varying degrees in the Canterbury region. Ground subsidence as a result of liquefaction-induced differential settlement, lateral spreading and ejection of liquefied materials were the principal ground deformation modes that caused damage to residential buildings in the region. As a result, about 8,000 residential houses have been abandoned following the earthquakes, while 20,000 houses were severely affected and an additional 60,000 houses were affected by the liquefaction (van Ballegooy et al. 2014).

In response to the CES, the Ministry of Business, Innovation and Employment (MBIE) had grouped the residential lands into four different zones (MBIE 2015): Green zone, where repair or rebuild process can begin; Red zone, where land repair would be prolonged and uneconomical; Orange zone, where further investigation and assessment are required to reclassify it as Red or Green zone; and White zone, which are still being mapped. Based on expected future liquefaction performance, residential lands in the Green zone were then assigned into three foundation technical categories: TC1, TC2 and TC3. These categories are described in Table 1, together with the minimum recommended vertical settlements to be used in foundation design for each technical category. Per the MBIE guidelines, the indicator criteria for foundation damage not requiring structural repair is settlement < 50mm and floor slope to be < 1/200 between any two points > 2m apart.

Table 1. Technical categories for rebuilding Christchurch and vertical settlement limits (MBIE 2015).

Technical Category	Description	Settlement limit*
TC1	Liquefaction damage is unlikely in future large earthquakes. Standard residential foundation assessment and construction is appropriate.	15mm
TC2	Liquefaction damage is possible in future large earthquakes. Standard enhanced foundation repair and rebuild options in accordance with MBIE Guidance are suitable to mitigate against this possibility.	50mm
TC3	Liquefaction damage is possible in future large earthquakes. Individual engineering assessment is required to select the appropriate foundation repair or rebuild option.	> 100mm

* under design serviceability limit state (SLS) event

Improvement of the foundation ground can effectively reduce liquefaction-induced ground deformation of houses to within acceptable limits. However, the depth of liquefiable soil in Christchurch extends to considerable depth and it is not practical to treat the entire liquefiable layer underneath a house to address the issue.

2 METHODOLOGY

To investigate the depth of ground improvement (GI) required to meet the settlement and tilt requirements as set out by the MBIE, numerical analyses were carried out using the two-dimensional finite difference program FLAC (Itasca 2014). It allows for input of seismic acceleration/velocity/stress time histories to model the cyclic behaviour of soils. Liquefaction was simulated using the Finn-Byrne (1991) model which was incorporated into the Mohr-Coulomb plasticity model in FLAC.

The recorded ground motions from three strong motion station (SMS) sites were used in the analyses: Riccarton High School (RHSC), Papanui High School (PPHS) and Kaiapoi North School (KPOC). These SMS sites were selected as no liquefaction has been observed at these locations. These motions, taken from the website of GeoNet (2014), were deconvoluted to the top of rock level using the program Strata (Kottke et al. 2013) and then used as base input motion in the FLAC model. Here, the compliant base deconvolution procedure proposed by Mejia & Dawson (2006) was adopted.

After conducting verification exercise to validate the model, a typical house on a representative site was considered, and the effects of various parameters, such as width and stiffness of ground improvement, input motion and liquefiable layer thickness, on the required improvement depth were analysed.

Note that the total settlements are relative to the original ground level and are the absolute settlements that have occurred. On the other hand, differential settlements are the difference in total settlements between foundation edges while floor gradients are calculated by dividing the differential settlement by the foundation width. These are illustrated in Figure 1. Further details of the assumptions, numerical models and input parameters are discussed by Zhang (2015).

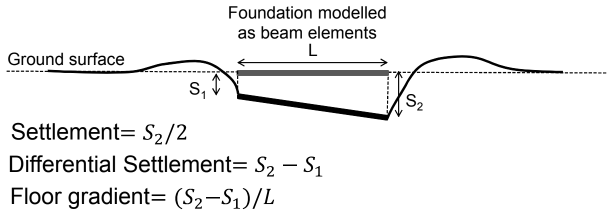

Figure 1. Definition of settlements and floor gradient.

3 NUMERICAL RESULTS

3 .1 *Verification exercise*

A two-stage verification exercise was first carried out to validate the numerical models used. The first stage involved the use of deconvoluted motion at RHSC site as base input motion in the FLAC model to analyse the response of the site. Resulting time histories and response spectrum computed at ground surface of the FLAC model were then compared with the actual recorded motions. In the second stage, the deconvoluted motion at rock level was applied to the FLAC model at Shirley Library, where moderate to severe liquefaction has been observed. Occurrence of liquefaction was checked using FLAC and resulting deformation at ground surface was compared with settlement estimates outlined in the Guidance formulated by MBIE (2015). All the soil profiles at the sites considered are available from Canterbury Geotechnical Database (CGD 2014). Due to space limitations, the results of the verification exercises are not presented herein; suffice it to say that the calculated results agreed very well with the observations.

3.2 *FLAC numerical analysis*

The target model ground for the analysis was located at the suburb of St Albans, classified as TC3 site. This site was selected because liquefiable soil extended to a considerable depth of 11m below ground level at this site and underwent significant liquefaction-induced damage during the CES.

After liquefaction was checked for this site using FLAC, a structural beam was placed at the ground surface to model the residential house foundation. For this purpose, an average-sized house measuring approximately 14m × 15m foundation footprint was considered. The beam was split into two segments and assigned different unit weights to model the possible differential loading of a two-storey building. Loadings of 10kPa for the first floor and 5kPa for the second floor were estimated for typical residential houses following NZ Standard (SNZ, 2002). The magnitudes of total and differential settlements of the foundation were computed before and after ground improvements are installed. Ground improvements are modeled as an equivalent block of material with specified properties.

A control model was set up with ground improvement properties as follows: density, ρ=2000 kg/m^3; shear wave velocity, V_s=200 m/s; maximum shear modulus, $G_{\max}$=80 MPa; friction angle, ϕ=42°; Poisson's ratio, ν=0.3. The improved section extended 2m beyond the foundation (a total width of 18m) and to a depth of 3m below ground level with the deconvoluted motion at RHSC applied as input motion (with PGA adjusted to 0.35g at ground surface). The ground improvement width and depth were based on the minimum required values set in the MBIE Guidance document (MBIE, 2015). The FLAC control model set-up is presented in Figure 2. The model was ran and resulted in settlement of 400mm, which exceeded the limit shown in Table 1. Analyses were then conducted to examine the effects of various parameters on the required GI depth, and the results are discussed below.

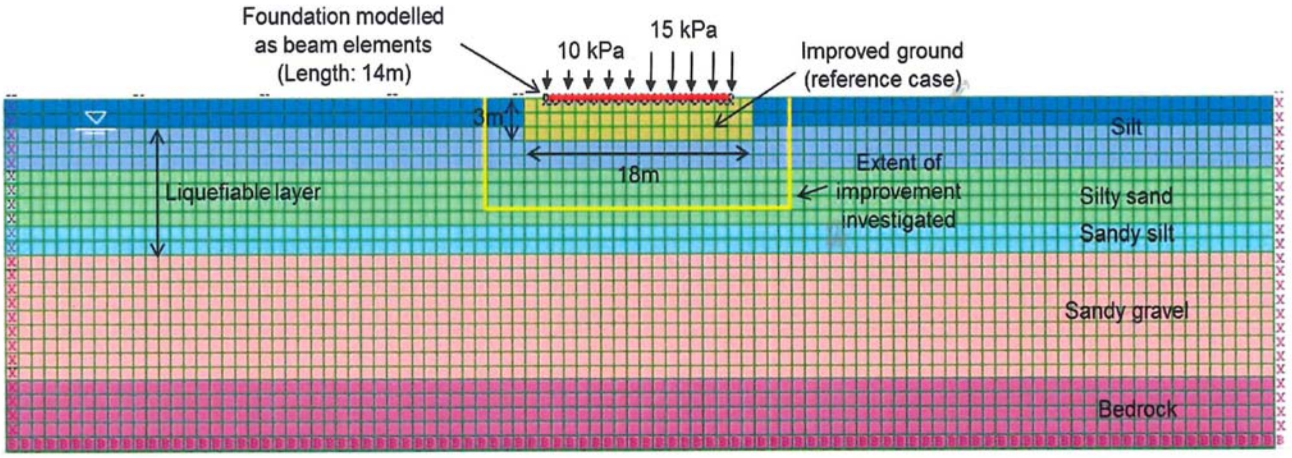

Figure 2. FLAC Control model at St Albans, Christchurch (each square mesh element is 1×1m in dimension).

3.2.1 *Effect of width of improvement*

The control model was considered and the GI width varied to 14m, 16m, 20m, and 22m. The same analyses were then re-ran with the results plotted in Figure 3. Note that some of the irregularities in the plots appear to be artefacts due to the nature of numerical modeling; hence focus is made on the general trends observed.

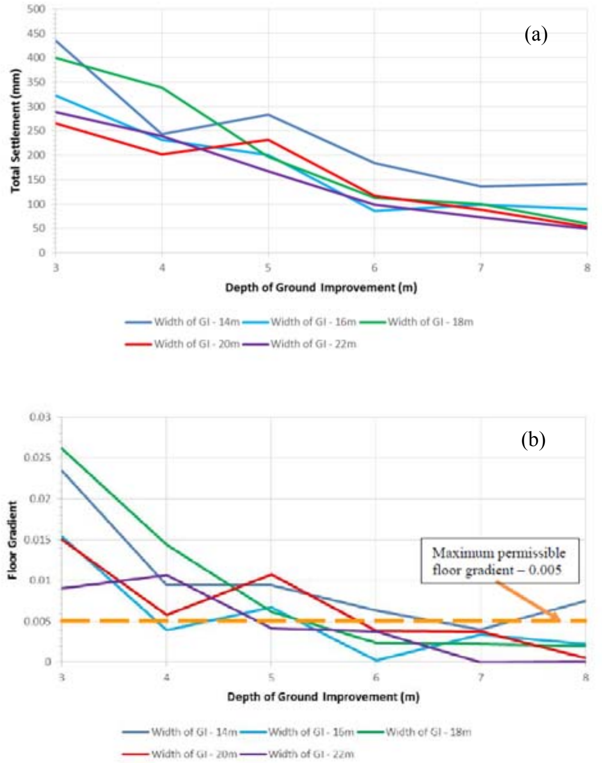

Figure 3. Effect of width of improved zone on: (a) total settlement; and (b) floor gradient with RHSC input motion.

As expected, the plots in Figure 3(a) show a decrease in settlement when the depth of ground improvement is increased. The rate of reduction in settlement decreases as depth of improvement increases and the trend starts to flatten out after 6m of improvement. The minimum depth to achieve settlement and floor gradient requirements is between 5 – 6m.

There is no notable trend relating the width to depth of improvement for less than 5m depth of improvement. When depth > 5m, it appears extending the improvement area by at least 1m beyond both sides of the foundation perimeter reduces the total settlement, although any further increase in the width of ground improvement does not show additional reduction in settlement. This observation is in line with the recommendation of extending the ground improvement 1 – 2m (depending on the method adopted) beyond the perimeter foundation line provided by the Guidance document (MBIE 2015). By extending the width of ground improvement, the influence of the surrounding unimproved ground on the foundation reduces and, based on the results, 1m is sufficient for the influence to become negligible. Note that the current FLAC models cannot take into account the possible softening of the improved ground as a result of pore water pressure migration from the untreated region to the improved zone.

3.2.2 *Effect of stiffness of improvement*

The control model was then duplicated but with the stiffness of the improved ground changed to 64.8MPa, 96.8MPa and 115.2MPa. The same analyses were re-ran with the results plotted in Figure 4, which show a decrease in floor gradient when the depth of improvement is increased. The rate of reduction in floor gradient decreases as depth of improvement increases and the gradient starts to flatten out after 6m of improvement. The minimum depth to achieve the floor tilt requirements is approximately between 4 – 5.5m.

Within the range of stiffness considered, there is no notable correlation between stiffness to depth of improvement. The analyses with different values of stiffness all show the same trend with some scatter, although the variations appear to be more of fluctuations due to the nature of numerical modeling. This implies that as long as the ground improvement has sufficient stiffness so that it does not liquefy or soften during a seismic event (as recommended by MBIE 2015), the deformation is mainly governed by the liquefied soil.

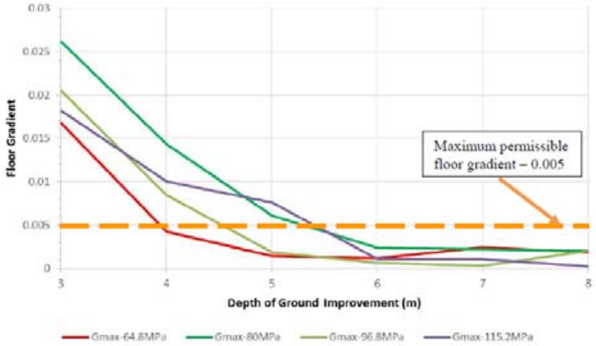

Figure 4. Effect of stiffness of improved zone on floor gradient with RHSC input motion.

3.2.3 *Effect of input motion*

Next, the same control model was considered and the seismic motions deconvoluted at PPHS and KPOC sites (with amplitudes adjusted to result in PGA=0.35g at ground surface) were applied as input motion in separate analyses. The results are plotted in Figure 5.

The plots show that different seismic motions cause different trends in floor gradient. Although not shown here, variations in both total and differential settlements were also observed. However, all the results exhibit similar trends and there appears to be a critical ground improvement depth where any further increase in the depth of improvement has limited influence on the resulting differential settlement. The minimum depth to achieve the differential settlement and floor gradient requirements is approximately between 5.5 – 7.5m; this difference in the required depth of ground improvement of 2m is fairly significant. One of the reasons for such difference is possibly due to the motions having different response spectra; although the motions were matched for PGA, they have different frequency contents and therefore they produced different response.

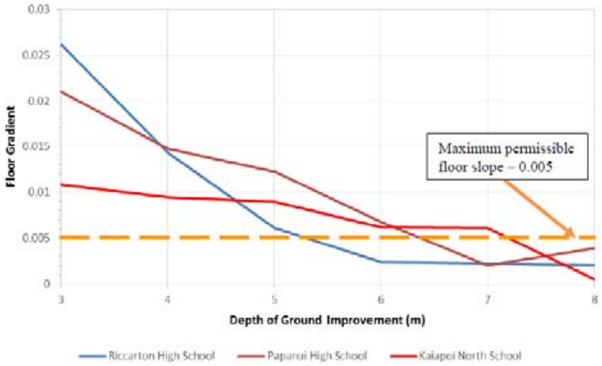

Figure 5. Effect of input motion on floor gradient.

3.2.4 *Effect of liquefiable layer thickness*

The control model was duplicated but with the thickness of the liquefiable layer changed to 7m, 8m and 11m. The same analyses were re-ran with the results plotted in Figure 6. Although the total settlement, which is not shown here, continues to increase as the liquefiable layer becomes thicker, there appears to be a limiting GI depth between 5 – 6m where the floor gradient trends start to flatten out. Any further increase in the liquefiable layer thickness beyond that does not seem to have any significant influence on the differential settlement.

This observation is in agreement with the chart developed by Ishihara (1985) to estimate liquefaction-induced damage using the thicknesses of surface non-liquefiable layer (H_1) and underlying liquefiable layer (H_2) and reproduced in Figure 7. Note that the proposed curves reach an asymptote when a certain thickness of non-liquefiable crust exists. The difference between Ishihara's chart and this study is that Ishihara's definition of non- liquefiable crust is for an infinitely long layer whereas the improved zone in this study is of finite width. However, as discussed above, as long as the improved ground is extended outside the foundation perimeter on both sides by at least 1 – 2m, any additional increase in the width of improvement does not affect the differential settlement. Therefore, the results of this study should be comparable to Ishihara's estimates. From Figure 7, approximately 7m thick layer of non-liquefiable crust is estimated to prevent ground damage for the control model (with PGA=0.35g), which is not significantly different to that predicted using FLAC.

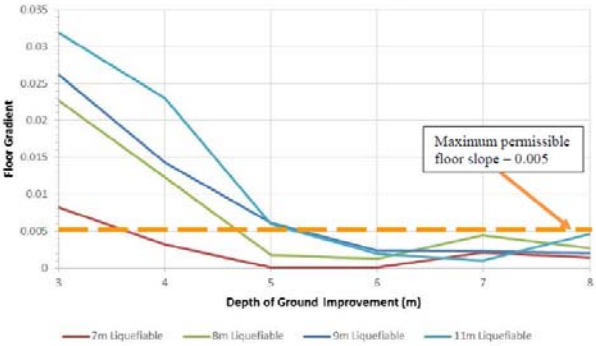

Figure 6. Effect of thickness of liquefiable layer on floor gradient with RHSC input motion.

3.2.5 *Summary of results*

The results of all the analyses were plotted onto Ishihara's chart as shown in Figure 7. Some interpolation was required and results from Sections 3.2.1 and 3.2.2 were not included as changes of width and stiffness of ground improvement did not seem to affect the required depth of ground improvement.

Results from Section 3.2.4 fitted reasonably with Ishihara's 0.3g curve, although the analyses performed do not cover the lower range of this curve. When different seismic motion records were used, results from Section 3.2.3 appear to show a shift towards the 0.4 – 0.5g curve. These observations seem to indicate that for Christchurch residential buildings, the response falls between Ishihara's 0.3g and 0.4 – 0.5g curves, indicating that the chart may be used for estimation purposes.

However, the chart should be used with caution as the findings presented herein were based on limited amount of analyses data and further research work in the future would be recommended to allow for better comparison. Such further work should include, among others, considering non-homogenous soil profile (or with G_{max} varying as function of in-situ effective stress) and incorporation of post-liquefaction reconsolidation settlement as the excess pore water pressure dissipates, which was not covered in this study.

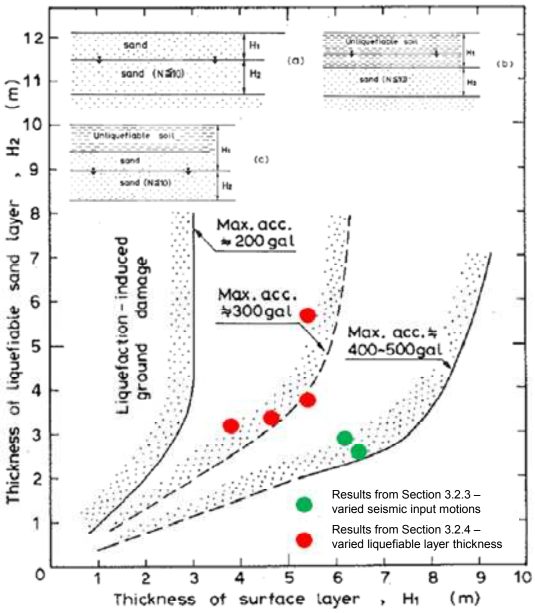

Figure 7. FLAC analysis results at St Albans plotted against Ishihara's chart (1985).

4 CONCLUSIONS

A study was conducted using the finite difference software FLAC to investigate the required depth of ground improvement for Christchurch residential buildings to meet the criteria set out in the guideline provided by MBIE. The major conclusions are:

- The width of ground improvement did not appear to affect the required depth of improvement, as long as it was extended by at least 1m beyond the foundation perimeter.
- There was no notable correlation between stiffness to depth of improvement, provided there was enough stiffness to prevent liquefaction.
- Varied seismic motion records produced different required improvement depths due to different frequency contents.
- When the liquefiable layer thickness was increased, the required GI depth increased up to a limiting depth.

5 REFERENCES

Byrne PM. 1991. A cyclic shear-volume coupling and pore pressure model for sand. *2nd Int. Conf. Recent Advances in Geotech Equake Engg and Soil Dyn*, St. Louis, Missouri, Paper No. 1.24, 47-55.

Canterbury Geotechnical Database, CGD 2014. https://canterburygeotechnicaldatabase.projectorbit.com/

GeoNet 2014. http://www.geonet.org.nz/

Ishihara K. 1985. Stability of natural deposits during earthquakes. *Proc. 11th Int. Conf. Soil Mech & Found Eng*, San Francisco, 321-376.

Itasca Consulting Group Inc. 2014. *FLAC Version 7.0 Manual.* Itasca.

Kottke AR, Wang X, Rathje EM. 2013. *Technical Manual for Strata.* University of Texas.

Mejia LH, Dawson EM. 2006. Earthquake deconvolution for FLAC. *4th Int. FLAC Symp. Numerical Modeling in Geomechanics,* Minneapolis, Paper No. 04-10.

Ministry of Business, Innovation & Employment 2015. *Guidance on Repairing and Rebuilding Houses Affected by the Canterbury Earthquakes.* Wellington.

Standards New Zealand 2002. Structural design actions Part 1: Permanent, imposed and other actions - *NZ Standard 1170.1.*

van Ballegooy S, Malan P, Lacrosse V, Jacka ME, Cubrinovski M, Bray JD, O'Rourke TD, Crawford SA, Cowan H. 2014. Assessment of liquefaction-induced land damage for residential Christchurch. *Earthquake Spectra*, 30(1): 31-55.

Zhang ZY. 2015. Mitigation of damages to residential buildings caused by liquefaction induced settlement in Christchurch, *Master Thesis*, University of Auckland.