Ground reinforcement with shallow timber piles for soils susceptible to liquefaction

A. Th. Giannakogiorgos[1], T. Nallarulanantham and S. Iyathurai[2]

[1]Coffey International Ltd, 131 Wrights Road, Addington, Christchurch 8024, New Zealand; PH +64 (0) 3 336 5472; email: Andreas.Giannakogiorgos@coffey.com
[2]Coffey International Ltd, 47 Doggett Street, Newstead, Qld 4006 Australia; PH +61 7 3608 2555; email: Thayalan.Nall@coffey.com; Sathananthan.Iyathurai@coffey.com

ABSTRACT

There is a growing interest to use short timber piles to "stiffen" soils that are susceptible for liquefaction as "vertical" soils reinforcement. The function of the timber piles is not to prevent liquefaction but to reduce the severity of consequences following liquefaction providing a more uniform response. During liquefaction there is a pronounced reduction in soil strength and stiffness (stiffness degradation). In such circumstances the presence of short timber piles in liquefied ground "increase" – alter ground stiffness and provide better stability to foundation system from displacement. Along with the gravel raft, the treated ground would behave like a stiffer crust above the liquefied deposits and tend to provide some beneficial effect to mitigate the mode of deformation induced by the liquefied soil.
Numerical modelling has been undertaken to investigate the system performance and to compare it with other layouts without the timber piles and / or the gravel raft.
This paper presents some of the findings of the numerical model and compares the degree – level of improvement that can be achieved by the use of short timber piles in liquefiable ground.
Results indicate that the grid of timber piles with the gravel mat provides better model performance in terms of displacement and improves the foundation behaviour.

Keywords: timber piles, liquefaction, numerical analysis, ground reinforcement

1 INTRODUCTION

Liquefaction is a phenomenon in which saturated cohesionless soils are subjected to a temporary, loss of shear strength due to incremental pore water pressure build-up during an earthquake (cyclic loading). It is generally known that saturated loose and uniformly graded fine-grained sands are susceptible to liquefaction. However field evidence suggests that strength and stiffness properties of loose silt and clay materials also get affected under cyclic loading and this phenomenon is termed as cyclic softening.

In engineering practice various ground improvement techniques are employed to reduce in-situ susceptibility for liquefaction and to improve soil conditions toward minimising the impact of liquefaction on foundation and structural performance. The liquefaction countermeasure techniques undertaken are primarily based on soil improvement and / or reinforcement by improving the strength, density and drainage characteristics of the soil.

Frequently used methods in soils susceptible for liquefaction are; stone columns, deep soil mixing and driven piles to provide support, improve strength and stiffness and provide adequate drainage paths. As part of the driven pile solution, embedded short timber piles are investigated in order to demonstrate the behaviour and to provide some insight of the mechanism.

Driven timber piles, have substantial service lives when installed beneath the permanent groundwater table (Studleim & Kleutsch - FY 2013 Research Problem Statement), and provide a significant reinforcement effect due to their inherent flexural rigidity and shearing resistance. Despite the densification that might occur under specific conditions, ground reinforcement is considered to be the most important element of the system's performance. Although little work has been done towards understanding the mechanisms involved using driven timber piles.

2 PILOT GROUND IMPROVEMENT TRIALS

On 22nd February in 2011, a magnitude M6.3, aftershock of the 2010-2011 Canterbury earthquakes, hit the Christchurch city in New Zealand, causing severe damages and loss of life. Damage observed in Christchurch was dominated by the effects of liquefaction-induced ground failures. Liquefaction-induced damages were significant to light residential structures throughout the city. Building damage was most pronounced in parts of the city with shallow liquefiable soils.

In November 2013, the Earthquake Commission (EQC) set about to undertake an additional pilot programme of ground improvement (GI) trials, within the Canterbury region (on vacant red zone properties in Avondale, Christchurch). The purpose of the GI trials was to provide a full-scale costing exercise for ground improvement techniques on properties located on the assigned TC3 areas where moderate to significant land damage from liquefaction is possible in future large earthquakes (as per Ministry of Business, Innovation and Employment (MBIE) Residential Foundation Technical Categories). This was done by competitively tendering and constructing various types of GI works on a variety of residential sites around Christchurch and Kaiapoi. Through the pilot programme construction specifications were developed for each of the GI techniques.

EQC's GI programme, run by leading experts from New Zealand and around the world, to trial a number of ground improvement methods that are tried and true in large scale civil construction projects, to see if they can be applied in residential construction in Canterbury. Several methods have being trialled under a controlled blasting programme on vacant properties in Avondale to test the effectiveness of methods that can be used to strengthen residential land vulnerable to liquefaction.

During those trials, an alternative method of driving 250mm diameter timber piles (3.6m long in a grid at 1.2m driven into the ground and capped with a 300mm gravel raft) within liquefiable ground was tested. Following the controlled underground blasting to trigger liquefaction, it has been found that the system performed particularly well (anecdotal information to date and inferred conclusion).

Even though the details of the trial study has not been published, it is known that driven timber piles is a method included in the draft Ground Improvement Standard Specifications for residential properties in Canterbury, together with Densified Rafts, Stabilised Crusts (in-situ and ex-situ mixed) and Stone Columns.

3 MODEL STUDIES WITH GROUND IMPROVEMENT PILES

Research and model tests to evaluate the performance of shallow ground improvement – treatment methods were carried out (Yoshida et al 2012 & 2013, Kiyota et al 2013, Willis 2013). Those studies concluded that soil improvement by means of individual piles is less efficient in mitigating liquefaction than the other techniques tested. While this might be the case for mitigating liquefaction, the effect of the driven piles on the overall foundation performance, under the prospective of soil reinforcement, hasn't been fully revealed.

The performance of a dwelling unit having an enclosed foundation with sheet piles installed to mitigate liquefaction-induced settlement has been studied by small shaking tables on model houses (Yoshida et al, 2012 & 2014). Yoshida also conducted a series of shaking table tests to understand the effectiveness of timber logs (piles) installed within the liquefiable ground by measuring the excess pore water pressures and vertical displacement. It has been found that the logs installed in the liquefiable ground increased the resistance against liquefaction by the following five mechanisms:

- Replacing part of the loose sand with the timber logs (area replacement ratio);
- Densifying the loose sand by the timber logs installation and "displacing" the soil particles laterally (and an increase - change in lateral stress [$\Delta\sigma_2$]);
- Restraining the shear deformation by fixing the top of the logs into gravel layer;
- Dissipating excess pore water pressures along the periphery of the piles;
- Reducing the magnitude of overall settlements

Closely spaced driven piles can increase the stiffness of the soil mass and significantly reduce differential settlements, and in the current study, we are not considering that piles will provide any kind of ground improvement and mitigation of liquefaction through densification to the treated area beneath the foundations.

4 NUMERICAL MODELING

A simple framework was adopted with representative stages in order to simplify the liquefaction process. The analysis allows simulation of the liquefaction process including build-up of excess pore water pressure, triggering of liquefaction and subsequent losses in strength and stiffness of liquefied soils. It provides a simulation of earthquake loads throughout the depth of the foundation soil by considering responses of individual layers.

Several analyses were performed using the Finite Element Code PLAXIS for Hardening Soil model with small-strain stiffness (HSsmall) in order to investigate the behaviour and provide an insight of the mechanism – system response involved.

The goal of this study was to investigate the behaviour of the composite timber - soil system under seismic loading and liquefaction with and without the inclusion of either the gravel raft or the timber piles.

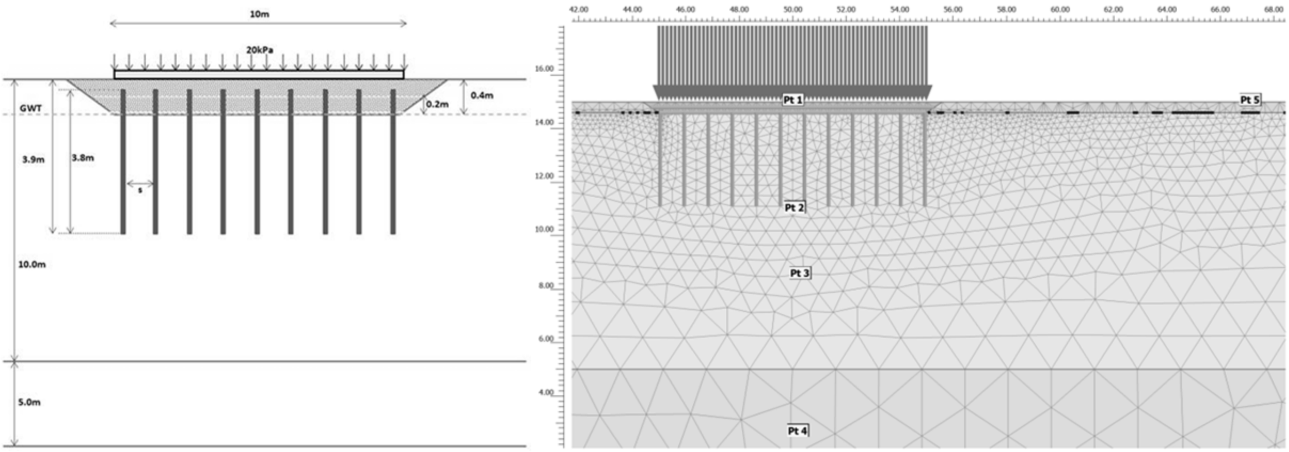


Figure 1. Schematic illustration of ground profile and finite element mesh used in Plaxis model

The configuration and soil parameters used are presented in Figure 1 and Table 1 respectively. The ground model consists of 10m thick liquefiable loose sand over 5m of dense non-liquefiable sand deposits . A 10m long spread footing exerting a bearing pressure of 20kPa on the underlying soil was modelled, over a 400mm thick geogrid reinforced gravel raft and driven timber piles (300SED) down to 3.9mbgl at 900mm spacing.

Table 1: Soil input parameters and soil properties employed in numerical analysis

	Layer		E	E_{lq}	G	G_{lq}	φ'	$φ'_{lq}$
	Top	bottom						(
	[m] bgl	[m] bgl	[MPa]	[MPa]	[MPa]	[MPa]	[^{o}]	[^{o}]
Loose Sand	0.0	10.0	11	1.1	55	5.5	29	15
Dense Sand	10.0	15.0	12.5		100		37	
Gravel raft			20		80		38	

For the input ground motion, the strong motion records from the Christchurch Hospital (CHHC station with a firm peak ground acceleration of 0.36g in the EW direction has been considered (Figure 2). CHHC seismic station was situated in a 2-storey concrete building (235 Antigua St) in the neighbourhood of Christchurch Hospital. The seismograph is placed on the ground floor.

Overall, the CHHC recorded shaking is a strong one, despite the relative low value of acceleration peaks. It should be noted that the recorded ground motions must have been somewhat affected by the structure response and cannot be characterized as true free-field records.

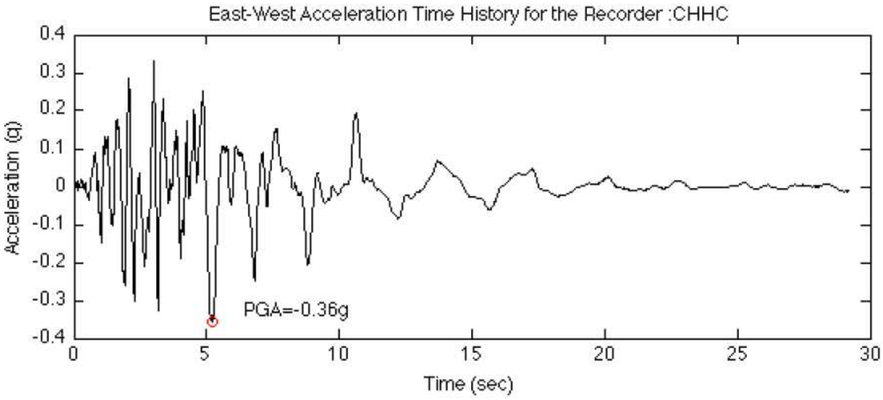


Figure 2. Horizontal acceleration input in Plaxis model (CHHC strong motion station, 22 Feb 2011 event)

The different composition of the spectral values for short and long periods in different regions in the city of Christchurch, can be partially attributed to source effects and to soil softening due to liquefaction that occurred (Smyrnou et al 2011) after 5 to 10 seconds of strong motion. Following that, our analysis process, towards simplifying liquefaction, consisted of bringing the soil to static equilibrium and then initiating dynamic shacking. After a pre-selected time (5 and 10 seconds used in our analysis) of strong shaking, liquefaction is triggered within the loose sand layer by significantly reducing shear modulus and strength due to liquefaction.

A minimum friction angle of 15 degrees for the liquefied sand was “required” to overcome bearing capacity failure without timber poles. The following sets of analysis were carried out with the soils parameters listed in Table 1:

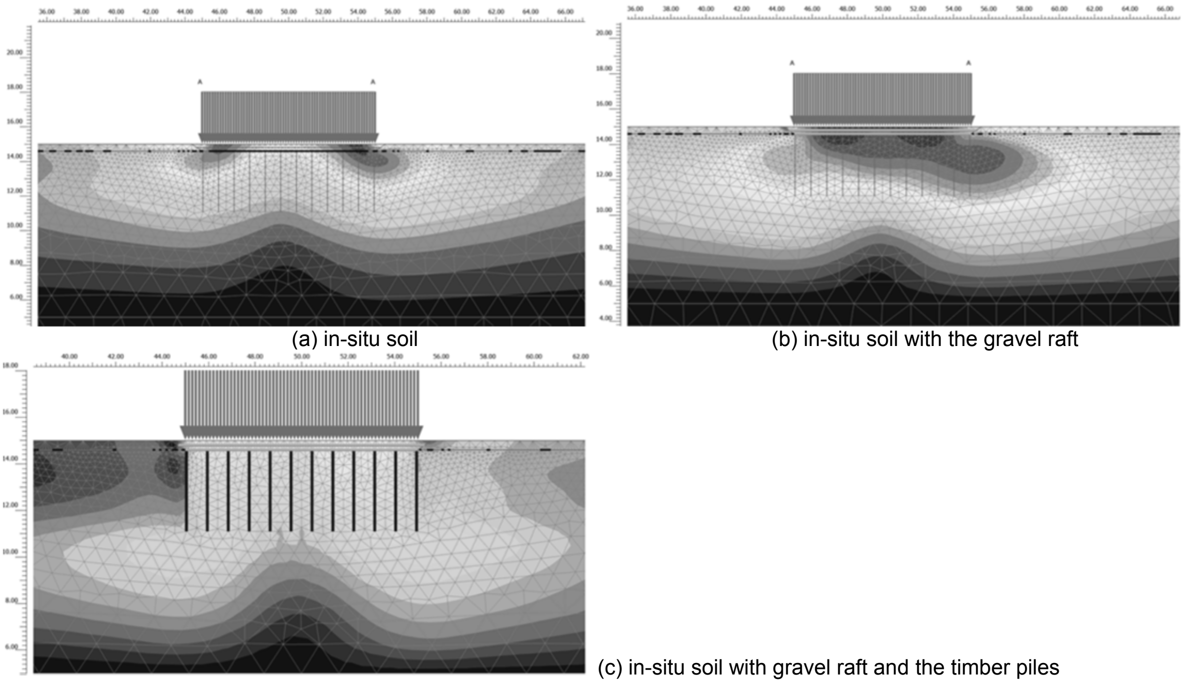
- Analysis # 01 – 20 kPa load over in-situ ground
- Analysis # 02 – 20 kPa load over soil raft
- Analysis # 03 – Timber piles were included for Analysis # 02
- Analysis # 04 – Drainage elements were included around the timber piles (add on Analysis # 03)

The comparison of excess pore pressure are indicative that the inclusion of the drainage element around the piles does not change the outcome and overall system performance in terms of limiting excess pore water pressure and calculated settlements. Figure 3 shows the graphical results in terms of calculated displacement contours.

The comparison between maximum vertical displacements for control point Pt1 (Figure 1) are given in Table 2 and these indicated that the predicted settlements decreased by 50 to 60% due to inclusion of the timber piles, with a more uniform response (Figure 3 and 4).

Table 2: Vertical displacement along the surface control point Pt1 in numerical model

Liquefaction at	Maximum Calculated Deformation (m)	
	Analysis # 01	Analysis # 03
0 sec	0.96	0.38
5 sec	0.52	0.22
10 sec	0.60	0.26



(a) in-situ soil
(b) in-situ soil with the gravel raft
(c) in-situ soil with gravel raft and the timber piles

Figure 3. Comparison of displacement contours

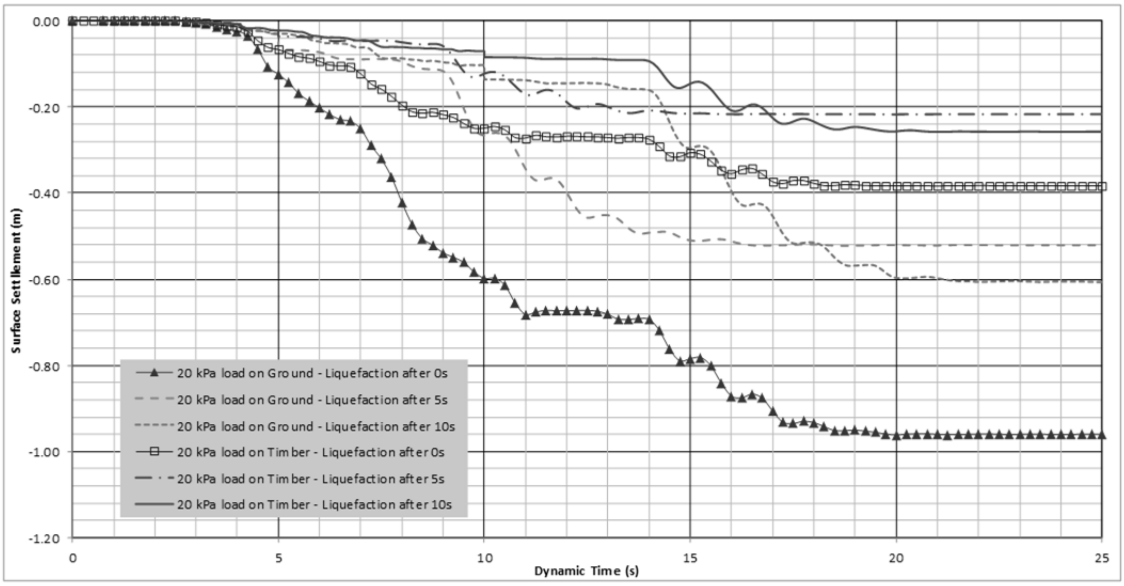


Figure 4. Calculated surface displacements histories with and without the timber piles

5 CONCLUSIONS

The behaviour of the system is evaluated through numerical simulation of a simple square spread footing over a saturated deposit of loose – liquefiable sand, as described in section 2.

In general the following can be summarized following our numerical analysis on the use of the timber piles:

1. *The treated ground would tend to act rather like a stiffer crust on the top of a liquefiable deposit, and so have some beneficial effect in this mode of action*
2. *There could be some, albeit minor, beneficial effects from the timber acting as a source of drainage and so helping to reduce the generated excess pore pressures*

3. *The treated zone would also tend to act as a stiffer raft and so help to reduce the impact of liquefaction from the soil below the treated area*
4. *Certainly, the presence of the gravel mat above the piles (with some geogrid reinforcement) is an important component of the system*

Even though the proposed simplified procedure of dynamic analyses did not capture every individual settlement mechanism accurately, the overall system performance with or without the inclusion of the timber piles can be comparatively evaluated in terms of anticipated displacements.

The analyses performed reveals that use of the timber piles plays an important role in reducing the liquefaction-induced foundation settlements to a considerable degree. Namely, with the installation of the timber piles and the reinforced gravel raft, the predicted settlement decreased by 50 to 60% with a more uniform response limiting the potential of differential foundation displacements.

6 ACKNOWLEDGEMENTS

The authors would like to specifically thank David Sullivan, Principal Geotechnical Engineer at Coffey, for his support supervising the research and providing valuable suggestions and comments.

REFERENCES

Kiyota, T., Tani, K., Matsushita, K., Hashimoto, T., Yamamoto, A., Takeuchi, H., Ohbayashi, J., Noda, T. and Kiku, H. (2013). "Mitigation of liquefaction-induced damage to residential houses by shallow ground improvement". New Zealand – Japan Workshop on Soil Liquefaction during Recent Large-Scale Earthquakes, December 2-3, 2013, Paper No. 14.

Smyrou, E., Tasiopoulou, P., Bal, I.E., Gazetas, G., Vintzileou, E. (2011). "Structural and Geotechnical aspects of the Christchurch (2011) and Darfield (2010) earthquakes in New Zealand". 7th National Conference on Earthquake Engineering, 30 May – 3 June 2011, Istanbul, Turkey.

Stuedlein, A.W. & Kleutsch, J.L.S. (2013). "FY2013, Research Problem Statement". Oregon Department of Transportation (ODOT) Research Section

Willis, M. (2013) "Empirical design and numerical modelling of timber piles employed as a liquefaction countermeasure". Bulletin of the New Zealand Geotechnical Society Inc., December 2013, Issue 86.

Wotherspoon, L.M., Orense, R.P., Jacka, M., Green, R. A., Cox, B. R., Wood, C.M. (*2014*). "Seismic Performance of Improved Ground Sites during the 2010–2011 Canterbury Earthquake Sequence". Earthquake Spectra: February 2014, Vol. 30, No. 1, pp. 111-129.

Yasuda, S. (2013). "New liquefaction countermeasures for wooden houses". New Zealand – Japan Workshop on Soil Liquefaction during Recent Large-Scale Earthquakes, December 2-3, 2013, Paper No. 15.

Yoshida, M., Miyajima, M., Numata, A. (2012). :Experimantal study on liquefaction countermeasure technique by Log piling for residential houses". 15th World Conference on Earthquake Engineering, September 24 to September 28, 2012, Lisbon, Portugal.

Yoshida, M., Miyajima, M., Numata, A. (2012). "Proposal of liquefaction countermeasure technique by log piling for residential houses". Matsue Conference Proceedings (The 10th International Symposium on Mitigation of Geo-disasters in Asia), 55-67

Yoshida, M., Miyajima, M., and Numata, A. (2013). "Application of Liquefaction Countermeasure Technique by Log Piling for Water Purification and Sewage Treatment Plant". International Efforts in Lifeline Earthquake Engineering: pp. 153-159