Densification of Liquefiable Soils using Driven Timber Piles

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ABSTRACT

The three most common ground improvement methodologies used by engineers to mitigate the potential damage from liquefaction include densification, drainage, and reinforcement. Conventional driven timber piles can be used as ground improvement by providing densification and reinforcement to the subgrade. Timber piles modified to provide drainage may be able to achieve all three improvement methodologies in one improvement method, or improve the magnitude of densification by virtue of relieving driving-induced excess pore pressure. Conventional and drained timber piles were installed to investigate the effect of pile spacing, time, and drainage on densification. Following installation of timber piles spaced at two, three, four, and five diameters, cone penetration tests were conducted at various durations following installation to evaluate the degree of densification, the effect of time, and the role of fines content on the degree of densification. In general, the relative density of the soils improved from approximately 40 to 50% pre-installation to 60 to 80% depending on the pile spacing and the presence of drainage elements. The effect of improvement on liquefaction resistances is described in terms of the factor of safety against triggering for each of the pile spacings.

Introduction

Among other recent earthquakes, the Canterbury sequence, largely characterized by four large (magnitude, M_w = 5.6 to 7.1) earthquakes between September 2010 and December 2011, highlight the significant damage to civil infrastructure that can be caused by liquefaction. The Christchurch event was characterized by significant and widespread liquefaction-induced damage to commercial structures, lifelines such as pipelines and bridges, and residential buildings, the latter of which suffered from ground subsidence, differential settlement, and lateral spreading with remarkable frequency and intensity (Van Ballegooy et al. 2014). These observations indicate a continuing need for the evaluation of cost-effective ground improvement methods to mitigate the effects of liquefaction. Common ground improvement techniques used to counter the effects of liquefaction fall into three general categories: densification, drainage, and reinforcement. Methodologies that can perform each of these functions, such as vibro-replacement (i.e., stone columns), represent desirable alternatives owing to the secondary effect of drainage in addition to densification and reinforcement. However, the performance of accepted techniques such as stone columns can suffer from inherent limitations, such as the reduction of densification and drainage capacity due to the presence of fines (Mitchell 1981), and the drainage effect is not typically incorporated into the design of liquefaction mitigation. The combination of ground improvement methods such as stone columns with pre-fabricated vertical drains (PVDs) has been shown to successfully improve densification in silty sands (Rollins et al. 2006, 2009). However, the use of more than one technique and its attendant equipment necessarily incurs greater mobilization, supply, and labor expenses, and may disqualify its use based on cost considerations.

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Oft-overlooked, driven timber piling has been shown to densify loose, sandy soils (Mitchell 1968). Despite the inexpensive nature of this renewable material, reservations against driven timber piles may stem in part from perceived long-term durability concerns or the usual questions regarding time-dependent densification (Mitchell and Solymar 1984, Slocombe et al. 2000) and the effect of fines impeding drainage thereby limiting the magnitude of densification. This paper presents a field trial of drained and conventional, driven timber piles conducted for the purposes of evaluating the magnitude of densification possible in soils considered to be susceptible to liquefaction. First, the subsurface conditions at the test site are described, including the development of a site-specific cone penetration test-based fines content correlation. Then, the liquefaction hazard for the test site is described in the context of the regional seismicity. Thereafter, the timber pile test program is presented, including the evaluation of PVDs fitted on timber piling for possible improvement in the magnitude and time-rate of densification. Comparison of improvement through densification is made as a function of pile spacing (ranging from two to five diameters, D), elapsed time-since-installation, and the presence of drainage elements. Observations derived from the test program show that significant magnitudes in densification, and thereby mitigation of possible liquefaction, can be achieved using driven timber piles.

Subsurface Characterization

The test site is located in Hollywood, South Carolina and is part of the Coastal Plain stratigraphic unit, which was formed by estuarine deposits (Doar and Kendall, 2014). The Lower Coastal Plain generally consists of Pleistocene age deposits, and specifically beach sands approximately 200,000 years old in the Hollywood region (Maybin and Nystrom 1997). The baseline (i.e., prior to pile installation) subsurface characteristics were evaluated throughout the various testing zones, described subsequently, using cone penetration tests (CPT), downhole shear wave velocity (V_s) tests, and standard penetration tests (SPT) within mud-rotary borings.

Figure 1 shows the subsurface profile across a 55 m cross-section of the test site prior to pile installation. The general stratigraphy consists of a 2 m thick layer of loose to medium dense silty and clayey sand (SM and SC) fill overlying 10 m of loose to medium dense, clean to silty fine sand (SP and SM) characterized with mean grain diameter of 0.2 mm. Below this potentially liquefiable soil unit lies several non-liquefiable strata including a layer of soft clay approximately 1 m thick, underlain by a 1.5 m thick deposit of dense sand, and followed by the marl of the massive Cooper Group. The groundwater table varied with precipitation events from approximately 2.5 m to 3.5 m below the ground surface during the exploration program, but did not vary spatially during a given day. Figure 1 shows the variation of corrected cone tip resistance, q_t, and energy-corrected SPT blow counts (N_{60}) with depth. In general, the potentially liquefiable layer is relatively uniform across the site with q_t ranging from approximately 1 to 10 MPa and 1 to 10 blows per 0.3 m (i.e., blows per foot), respectively. The in-situ tests correlate to initial relative densities of approximately 40 and 50% were estimated between the depths of approximately 3.5 to 11.5 m using (Mayne 2007):

$$D_r(\%) = 100 \left[0.268 \ln \left(\frac{q_t / \sigma_{atm}}{\sqrt{\sigma'_{vo} / \sigma_{atm}}} \right) - 0.675 \right]$$

(1)

where σ'_{vo} = effective overburden stress and σ_{atm} = atmospheric pressure. The effect of fines content, FC, on the triggering of liquefaction has been recognized for some time (e.g., Seed et al. 1985). Owing to the usefulness of the CPT for stratigraphic profiling, Robertson and Wride (1998) proposed a global CPT-based FC correlation using the soil behavior type index,
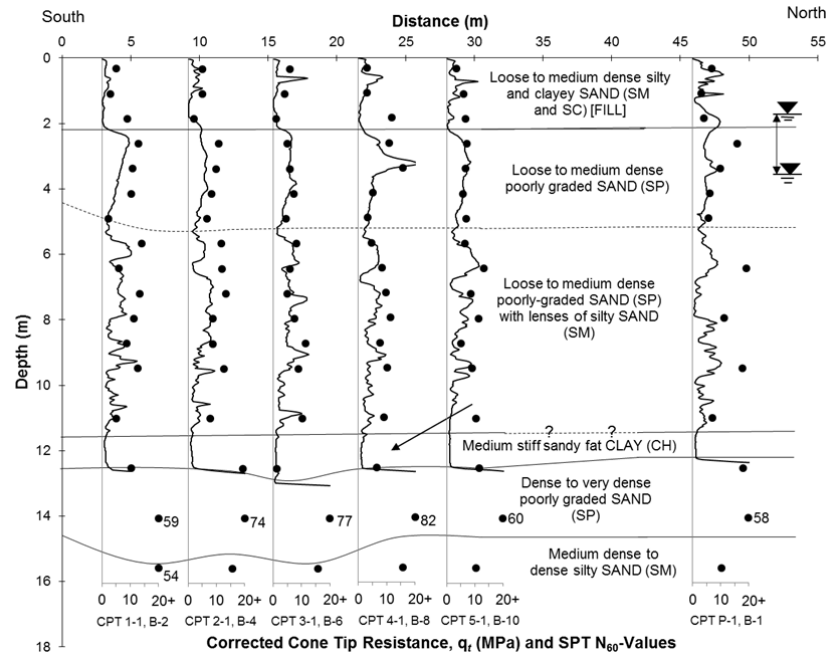
Figure 1. Subsurface cross-section of the test site. The surficial fill consisted of housing debris from Hurricane Hugo, and required drilling and spudding to penetrate

I_c, to make estimates of fines content in the absence of soil samples and their impact on liquefaction triggering. It has since been recognized that generic correlations to fines content may not provide sufficient accuracy and that the development of site-specific correlations are preferred (Robinson et al. 2013, Boulanger and Idriss 2014, Green et al. 2014). The functional form of the *FC* correlation proposed by Boulanger and Idriss (2014) was fit to the fines content of approximately 140 split-spoon samples, to result in the site-specific *FC* correlation suitable for the beach sands of coastal South Carolina:

$$FC = 54 \cdot I_c - 101 \tag{2}$$

Liquefaction Hazard at the Test Site

South Carolina is home to a regional seismic hazard that has been recognized since the 1886 Charleston Earthquake, an event that triggered widespread liquefaction (Hayati and Andrus 2008). The approximate magnitude of the Charleston Earthquake ranges from M_w = 6.9 +/- 0.3 (Bakun and Hopper 2004) to 7.3 +/-0.3 (Frankel 2002), and resulted in 124 deaths and significant damage estimated equal to US $460M (in 2006 dollars; Côté 2006). Marple and Talwani (2000) point to the Woodstock fault, which is part of the East Coast fault system and is approximately 600 kilometers in length, as the source of the 1886 rupture. The Woodstock fault is a strike-slip fault moving in the west-northwest direction (Marple and Talwani 2000, Hayati and Andrus 2008). In effort to compare liquefaction susceptibility of the soil before and after pile driving, the seismic hazard for trigger liquefaction analyses was estimated using the USGS probabilistic seismic hazard deaggregation (Petersen et al. 2008) and the Boulanger and Idriss (2014) procedures. Gianella (2015) evaluated two earthquake events for comparison: the 10% probability of exceedance in 50 years, and an estimate of the 1886 Charleston earthquake, corresponding to Events 1 and 2. For brevity, only Event 1, characterized with a PGA of 0.16g and M_W = 7.0, is discussed herein. Approximately one-half to three quarters of the liquefiable soil layer could be expected to liquefy, for the SPT and CPT procedures, respectively, for Event 1.

Driven Timber Pile Installation and Sequence

Investigation of Prototype Suitability

The typical dimensions of the timber piles used in this research, determined by measuring 33 randomly-selected piles, were characterized with and average length, head diameter, and toe diameter of 12.28 m, 0.31 m, and 0.21 m, respectively. In order to evaluate the integrity of the drains during installation of the drained timber piles, a test pile was driven and closely observed. The test pile prototype was created by wrapping pre-fabricated vertical drains (PVDs) around the tip of the timber pile and connecting it along the length of the pile using roofing nails as shown in Figure 2. The PVDs consisted of high-discharge polypropylene core channels wrapped with non-woven geotextile fabric (model MD-88, fabricated by HB Wick Drains) to prevent clogging of drains. The first test pile driven encountered difficulty, characterized by severing and buckling of the drain material during driving. After the pile was retrieved it was observed that the PVD was sliced and timber pile damaged by debris buried in the fill (Figure 1). In order to prevent similar damage from occurring for the production piles, additional roofing nails were added near the base of the pile, and pile locations were conditioned by pre-drilling a 241 mm diameter hole 2 to 3 m depth (depending on drilling response) and spudded where drilling refusal was encountered. No further damage to the drained piles was noted as a result of debris in the fill; however, very hard driving induced by effective densification did over-stress and damage several piles.

Ground Improvement Test Plan

The timber pile test area consisted of five zones that proceed from the south (Zone 1) to the north (Zone 5). Each zone was intended to consist of a 5x5 pile group with four "rows" and four "columns" (Figure 3). Zones 1 and 2 were used to evaluate drained timber piles spaced at 5D and 3D, respectively. Zones 3, 4, and 5 consisted of groups of conventional driven timber piles spaced at 5D, 3D, and 2D and 4D, respectively. Initially, Zone 5 was planned to consist of just 2D spacing, but as result of substantial densification and significant driving difficulty, the spacing was altered to 4D to provide improved resolution of spacing effects (Figure 4). Zones 1 through 4 and Zone 5 consisted of 25 and 33 piles each, respectively.

Effect of Spacing, Drainage, and Time on Densification

In order to evaluate the effect of spacing, time, and drainage on the amount of soil densification, an in-situ test plan was created to compare to baseline tests conducted prior to ground improvement. Four "cells" designated by column and row headings (e.g., B3, C3) in the middle of each pile group were selected to represent a theoretically uniform level of ground improvement within the pile group. Table 1 indicates the average number of days that the CPT soundings were performed following pile installation and the cell locations corresponding to Figures 3 and 4. Sounding A was pushed first in each cell and represents the midpoint between piles (and therefore the lowest expected quantity of densification) so as to compare to the initial improvement without the possible effects of the CPT-induced densification on neighboring soundings (e.g., soundings B and C; see Figure 5). Focusing on the data obtained from sounding A in each cell for simplicity, Figure 6 presents the pre-improvement baseline, the post-improvement at 49 days, and the predicted post-improvement D_r.

The D_r improved to approximately 70 and 80% in Zones 3 and 4 (5D and 3D spacing), respectively, in the upper 2.5 to 5 m, and to approximately 60 to 75% in the range of depths

Figure 2. Drained timber piles and PVDs used in this study

Table 1. Location of CPT's following timber pile installation.

Time Following Installation	Cell Locations (Zones 1 through 4)	Cell Locations (Zones 5A and 5B)
10 days	B2	B3 and E1
49 days	B3	B4 and E2
115 days	C2	C3 and F1
255 days	C3	C4 and F2
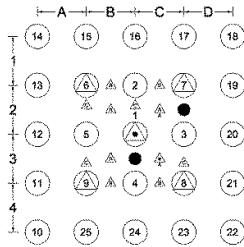
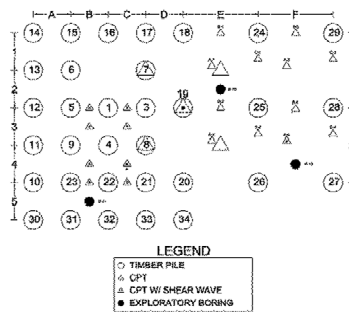Figure 3. In-situ test plan for Zones 1 through 4

Figure 4. In-situ test plan for Zone 5

Figure 5. Enlarged sketch of cell B2 in Zones 1 through 4

of 5 to 9 m for both pile spacings. Initially, the D_r in these zones ranged from 40 to 50%, resulting in absolute increases in D_r of 20 to 40%. The 49-day CPT soundings in Zone 5A and 5B at spacings of $2D$ and $4D$, respectively, refused between depths of 4 and 6 m below grade. Figure 6 shows that D_r in these zones was expected (i.e., predicted) to reach between 80 to 100% based purely on consideration of volume replacement by assuming that the volume of soil voids would be reduced by an amount equal to the volume of the pile distributed equally across the respective tributary area. This approach required the establishment of minimum and maximum void ratio. The average timber pile taper, equal to 25 mm per 3 m, was taken into account in the volume replacement-based relative density computations, as did the individual depths of the pile toes in each cell. The predicted D_r using the volume replacement approach varied for each cell with identical pile spacing, due to differences in the final pile toe elevations for each zone as shown in Figure 6. The expected and observed improvement decreases with depth as a function of the pile taper and increasing fines content. The increase in relative density estimated using the volume replacement approach is consistent with CPT refusal. Similar refusal depths were expected for the 115-day soundings in Zones 2, 4, 5A, and 5B based on volume replacement of the pile, and all soundings except in Zone 1 refused short of the target depth of penetration (i.e., 12.5 m). The 255-day soundings were offset a few inches if premature refusal occurred, and the desired penetration depth of approximately 12.5 m below grade was reached. To quantify the average
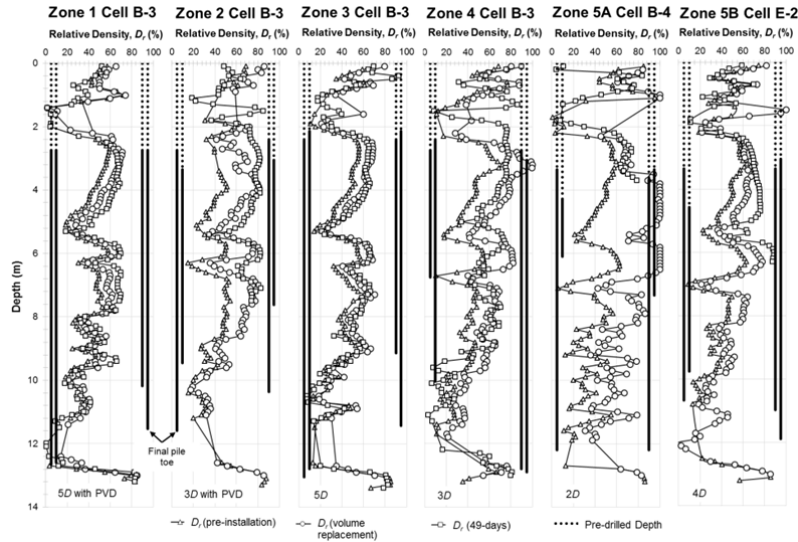
Figure 6. Relative density of ground prior to and 49 days following timber pile installation as correlated from cone tip resistance and theoretical volume replacement

improvement of each zone based on penetration resistance, a geometric mean was performed on the CPT q_t over a 0.16 m interval for depths evaluated for liquefaction hazard analysis (i.e., 3.3 m to 11 m). This allowed for the pre- and post-improvement q_t at 10 and 255 days to be compared directly accounting for minor spatial variability between the soundings. Table 2 presents the pre- and post-installation geometric average of q_t in each zone. The percent increase in q_t ranged from approximately 27 to 202% with the largest improvement in Zone 2 consisting of drained piles at 3D spacing. Table 2 shows that the drained piles (Zones 1 and 2) exhibited larger increases in q_t than the conventional piles. The improvement observed with the drained piles shows that the drains are effective for increasing the densification in fine sands as well as silty fine sands, soils that are often difficult to densify with other improvement techniques.

In order to evaluate the effect of time on the amount of soil densification the drained piles in Zones 1 and 2 (5D and 3D, respectively) are compared to the conventional piles driven in Zones 3 and 4. Figures 7 and 8 compares the D_r for each zone and for the 10-day, 49-day, 115-day, and 255-day soundings and post-improvement factor of safety against triggering of liquefaction, respectively. The effect of time-since-installation is expected to have little effect on the clean sands because densification occurs nearly instantaneously, but is expected to have a larger impact on the densification of the silty zones. The fines content increases to approximately 50% and 30% at depths of 5.25 m and 6.5 m below the ground surface, respectively. At these elevations, the 49-day D_r in Zone 2 has approximately a 5 to 10% larger improvement compared to Zone 4 with conventional piles. The improvement was generally the same when comparing Zones 1 and 3 at 5D spacing in these silty regions. After 115 days, the improvement in the silty zones is difficult to quantify because the soundings did not reach the target depth. Soundings in Zones 1, 3, and 4 penetrated the silt lens (~5.25 to 5.5 m below grade), and the post-improvement D_r at 115 days increased slightly as compared to 49-day, but it is difficult to ascertain the improvement between the drained and conventional piles at 3D owing to the early CPT refusal at approximately 3 m.

In general, D_r was the largest just following pile installation (i.e., after 10days), and appeared to decrease with time to the 255-day soundings. Exceptions are noted for the piles spaced at 3D (Zones 2 and 4) below approximately 7 to 9 m. Figure 7 shows indicates that some

Table 2. Average improvement in q_t using a geometric mean approach for the liquefiable soil layer thickness. Note 10-day soundings in Zone 5A (2D spacing) refused at shallow depths

Zone #	Average pre-treatment q_t (MPa)	Average post-treatment $q_{t,10\ days}$ (MPa)	$\Delta q_{t,10\ days}$ (%)	Average post-treatment $q_{t,255\ days}$ (MPa)	$\Delta q_{t,255\ days}$ (%)
1	4.9	7.6	57	6.1	27
2	5.0	15.0	202	12.3	147
3	5.3	10.2	93	6.9	31
4	4.7	12.0	156	10.5	124
5A	5.3	-	-	13.1	147
5B	5.7	11.3	98	7.2	27

occurs within the improved following installation, attributed to reduction in lateral effective stresses (Gianella 2015). This trend is also shown in Table 2, where the average change in q_t decreased by approximately 30 to 70% between 10-day and 255-day soundings depending on the pile spacing and presence of drainage elements.

As shown in Figure 8, the post-improvement factors of safety (FS) against liquefaction for Event 1 are generally larger than the pre-improvement FS. Zones 2 and 4 at 3D spacing showed much larger FS against liquefaction triggering compared to the FS of Zones1 and 3 at 5D spacing. The extent and magnitude in the increase in FS using the drained timber piles is noticeably larger than with the conventional piles. This indicates that post-liquefaction volumetric strains and corresponding settlements, or lateral spreading displacements, are expected to be smaller when using drained timber piling. Generally, earth structures such as approach fills or abutments founded on conventional or drained timber piles (e.g., pile embankments) would be expected to exhibit less surface expression of settlement if designed with an appropriate load transfer platform (i.e., basal reinforcements and/or pile caps).

Summary and Concluding Remarks

This paper presented the site characterization and results of an on-going field trial of novel, drained and conventional driven timber piles installed to evaluate the degree of densification and liquefaction mitigation possible with these methods. Based on the information collected to date, the following observations may be concluded:
1. A site-specific CPT-based fines content correlation suitable for beach sands of South Carolina was developed and confirms the necessity for development of geology-specific fines content correlations.
2. The relative density of liquefiable soils reached 60 to 100% (i.e., increase in relative density of 20 to 60%) following installation of timber piles, depending on the pile spacing and use of PVDs.
3. Drained piles at both 3D and 5D spacing exceeded the improvement expected by means of volume replacement; while the conventional piles improvement were less than or equal to the volume replacement estimation.
4. CPT soundings indicate improvements in q_t in the liquefiable soil layer of approximately 100% with a maximum average improvement of 200% for drained piles at 3D spacing.
5. Comparison of FS against liquefaction for one earthquake event indicated that all of the test zones exhibited improved liquefaction resistance, but that zones with drained piling may perform the best with regard to post-shaking displacements.

Blast-induced liquefaction of a unimproved (i.e., control) zone and the same charge weights will be applied to the improved zones to make one-to-one comparisons of pore pressure

generation and determine the degree to which liquefaction is mitigated with respect to dynamic loading.
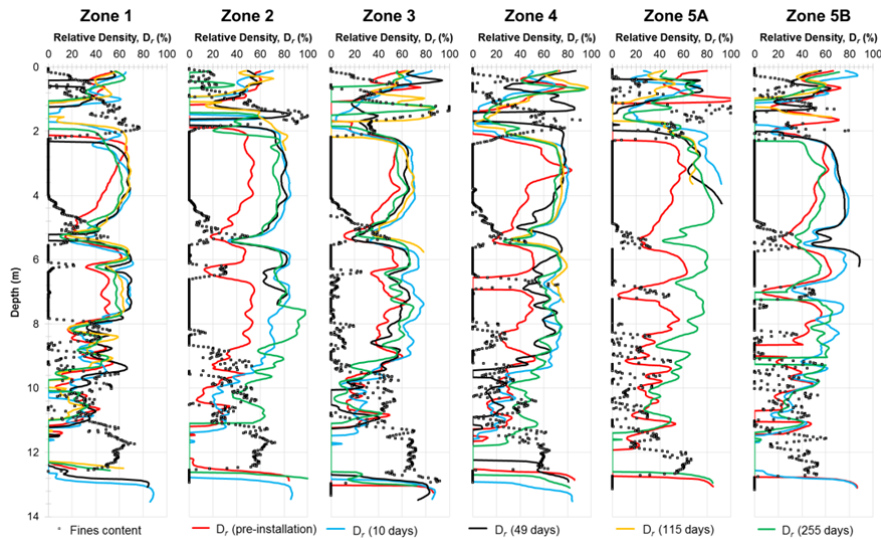

Figure 7. Baseline and time-elapsed post-improvement relative density and fines content as correlated from cone tip resistance
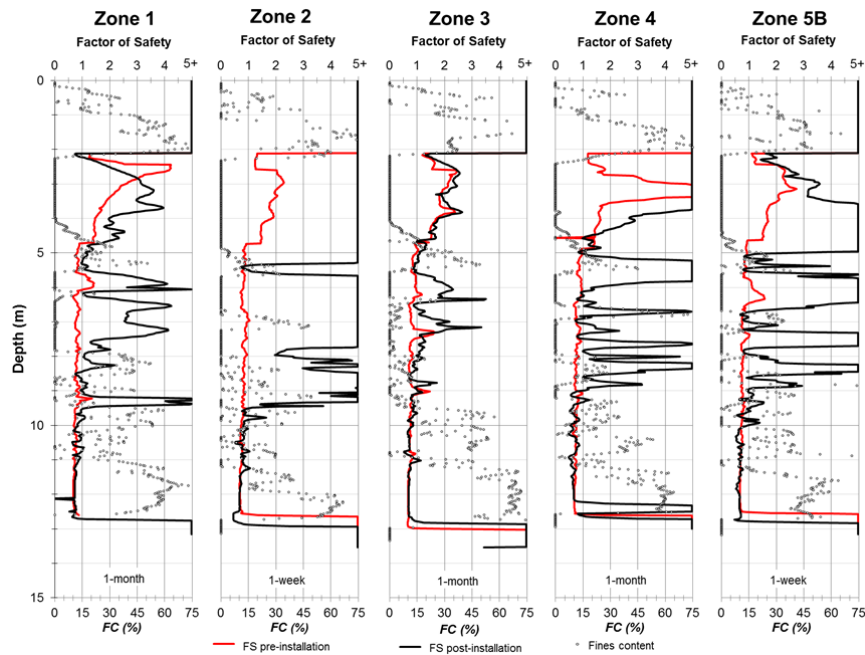

Figure 8. Pre- and post-improvement factor of safety (FS) against liquefaction for Event 1 using the Boulanger and Idriss (2014) procedures

Acknowledgements

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