The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2

Effect of pile shape on effectiveness of ground improvement by compaction piling

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ABSTRACT: Better understanding of seismic risk and the increasingly stringent design criteria in modern earthquake design codes have led to a need for technically sound and cost-efficient approaches to remediate existing infrastructure. Ground improvement by compaction piling is one of the methods used to densify and increase the resistance of loose sands to liquefaction, particularly where there is headroom restriction. Experience gathered during the seismic remediation of the Mission Bridge in Abbotsford, B.C., Canada, has suggested that the shape of driven piles has a marked effect on the degree of ground improvement achieved. In particular, the results from cone penetration tests have suggested that the driven (tapered) timber piles are more effective in densifying the ground in comparison to simply straight cylindrical concrete piles. A research program was undertaken to evaluate the reasons for this apparent difference in the effectiveness between tapered piles and cylindrical piles. As a first step, the available field penetration test data along with observations on the pile driving resistance, pile spacing and installation sequence, as well as the timing of quality assurance testing relative to the time of pile installation, were reviewed in detail. This paper is intended to summarize the findings from the above work.

1 INTRODUCTION

The Mission Bridge, which was built between 1968 and 1973, over the Fraser River is a critical link in the disaster recovery network of British Columbia. The bridge connects the District of Mission to the City of Abbotsford. The four-lane bridge is 1050 m long and is supported on a series of concrete bents or piers founded on steel piles. The seismic performance of the bridge was evaluated, and structural and geotechnical retrofit and rehabilitation measures were recommended to meet the safety level of the bridge to sustain a 475-year return period earthquake with magnitude M7.

The bridge site is underlain by potentially liquefiable Fraser River sand and liquefaction with potential lateral spreading is the key issue affecting the seismic performance of the bridge. The seismic retrofit strategy included vibro-replacement, compaction piles, compaction grouting, seismic drains and toe berms (Thavaraj et al., 2018). At the south river bank, specifically in pier S4, timber and concrete piles were selected as potentially viable methods to densify the soil under the bridge deck, and a test pile program was conducted.

Assessment of the test compaction pile program was based on cone tip resistance achieved. The results were interpreted to indicate that the shape of driven piles had a marked effect on the degree of ground improvement achieved. It appeared that the tapered timber piles were more effective in densifying the ground than the straight-sided cylindrical concrete piles. As a result, timber compaction piles were chosen to densify the soil under the bridge deck, where other alternatives were not considered because of headspace limitations.

Several studies have been made of the mechanics behind the effects of different shapes of driven piles. Lobo-Guerrero & Vallejo (2007) studied the influence of the pile tip shape and pile interaction around driven piles through a DEM analysis. Advanced model testing has been done to study how driven piles function and perform in sand (Jardine, 2014), including the measurement of displacement and strain paths during pile installation (White & Bolton, 2004), establishing stress conditions around displacement piles (Jardine et al., 2013), and centrifuge testing (El Naggar & Sakr, 2000). Additionally, experimental evidence of the penetration mechanism of a displacement pile has been obtained using transparent soils (Omidvar et al., 2016). Analytical solutions developed to predict the behavior of tapered piles (Liu et al., 2012; Salgado, 1997) and instrumented field tests (Stuedlein et al., 2016) have also contributed to this understanding.

This paper summarizes field observations before and after densification in the form of cone penetration test results, and the gathered data are analyzed to improve the understanding of the results obtained. Key factors include pile spacing, installation sequence and timing of quality assurance relative to the time of pile installation. This study aims to advance the understanding of ground improvement techniques by compaction piling.

2 COMPACTION PILING TECHNIQUE

Driven displacement piles of different materials and shapes have been used worldwide as compaction piles to improve ground and mitigate liquefaction. Piles are installed to a target depth using impact or vibration hammers. This process displaces the soil laterally, generally resulting in both densification and reinforcement of the material treated.

The prediction of the effects of driven displacement piles involve a significant degree of uncertainty due to high variability of the site conditions and the lack of understanding of the mechanics of the densification. Yang et al. (2014) emphasize that, in practice, the stress changes due to load cycles imposed during installation and time effects are generally neglected. One overlooked factor may be the mechanism resulting in "friction fatigue" defined by White & Bolton (2004), a reduction of shaft friction as the pile penetrates the ground under cyclic shearing induced by repeated hammer blows. Under this process, cyclic shearing occurs at the pile-soil interface, and different responses may be expected in the soil around a tapered pile compared to the soil around a straight-shafted pile.

3 PROJECT DESCRIPTION

3.1 *Soil conditions*

The geological profile at the south approach includes, from the most recent to the oldest deposit, surficial Fraser River sediments (unit 1) consisting of a silt layer of about 6 m thickness with an underlying sand stratum (unit 2) of post-glacial Fraser River sediments that varies from 21 m to 32 m in thickness. Unit 2 shows an upper layer of 10 m of loose deposits of a mixture of sands and silts, and then mostly medium dense sands, over an underlying layer of post-glacial fine-grained material including silt and clay at some locations and bedrock at others. Generally, the sand deposits at the south approach are looser and extend to greater depth compared to the north approach, justifying the additional studies that were done in the south approach to mitigate liquefaction.

3.2 *Compaction test pile program*

During the detailed design, a compaction test pile program was conducted in the south approach at the Pier S4. Timber and concrete piles were selected as potential compaction piles under the bridge deck with limited clearance. The test program consisted of evaluating pile drivability and effectiveness of the different compaction piles. Pre and post-treatment cone

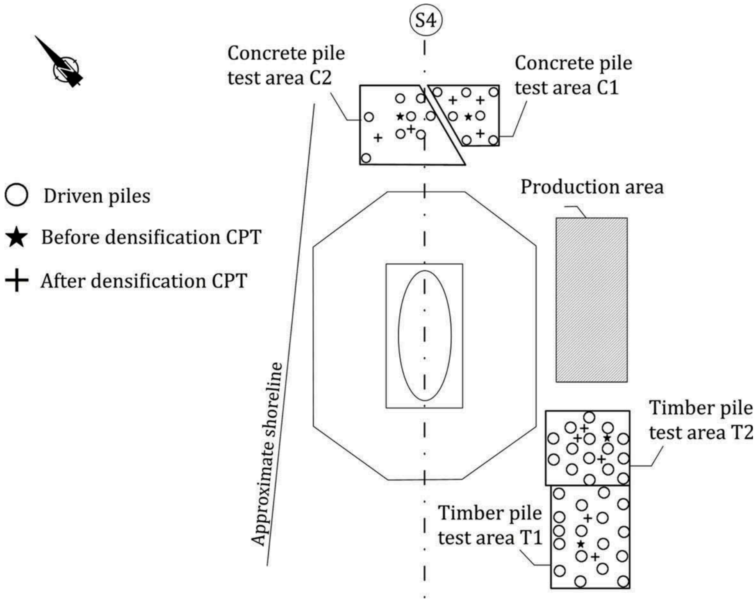


Figure 1. Location of densification areas

penetration tests were conducted to assess the improvement achieved. Figure 1 shows the location of Pier S4 in the project, and the concrete and timber pile test areas along with the subsequent production area.

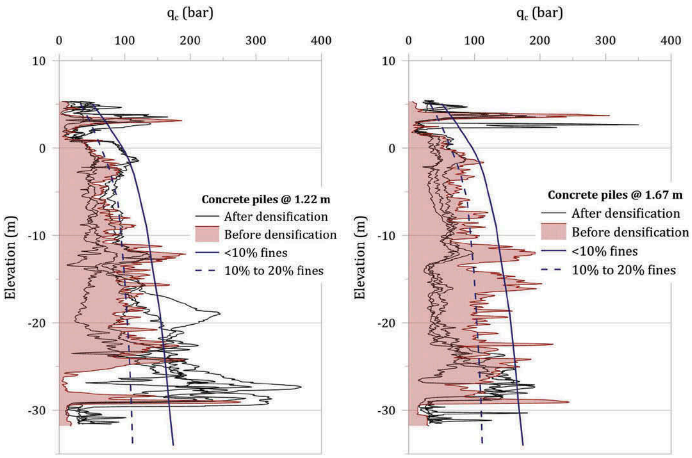
High Performance pre-tensioned spun concrete cylindrical piles of 350 mm outside diameter and 70 mm wall thickness were driven at the northeast side of pier S4 in two test sections, C1 and C2. A full end plate was welded to the bottom prior to driving. Piles were driven at 1.67 m centres in area C1 and at between 1.22 m and 2.4 m in C2. Each pile was 12 m long and so splicing was required to reach the target depth of 34 m. A total of 15 concrete piles were driven. Two CPTs were done pre-densification and 7 CPT were done after.

Douglas Fir timber compaction piles were driven southwest of pier S4. Spacing varied between 1.22 m and 1.52 m in the sections T1 and T2, respectively. The timber tapered piles were untreated, peeled round wood piles with toe diameter between 255 mm and 330 mm, and pile top diameter between 330 mm and 380 mm. The target depth was approximately 22 m, reached by two piles joined with steel tube splices. A total of 30 timber piles were driven and 2 CPTs were done pre-densification and 5 CPTs were done post-densification.

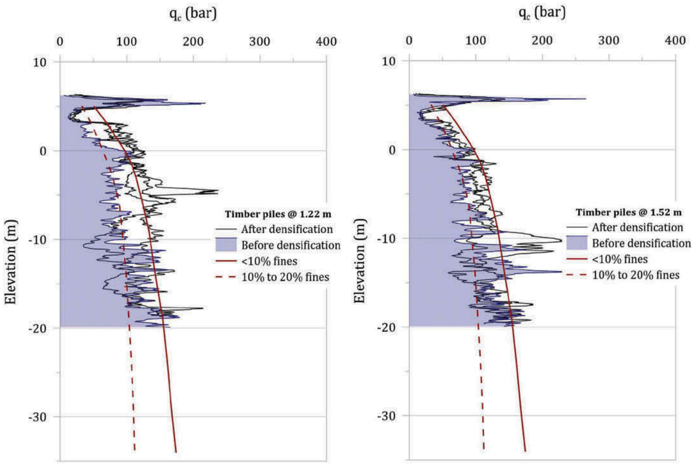
Pre and post cone penetration tests were used to assess the effectiveness of each type of pile for densification of the in situ soils. Figure 2 shows the comparison of the pre and post cone tip resistances for concrete piles (Figure 2(a)) and timber piles (Figure 2(b)); and the required minimum tip resistances for the corresponding soils with less than 10% fines, and 10% to 20% fines. The plots are shown for the spacings noted in Figure 2.

For the concrete piles test area, there is a significant reduction in tip resistance for spacings greater than 1.67 m (s/d=4.5), resulting in tip resistances less than the cone penetration tests done before the ground improvement. For closer spacing of 1.22 m (s/d=3.6), the penetration resistance does not exceed those recorded before the ground improvement. This suggest that spacings smaller than 1.22 m will be needed for concrete piles to achieve the requirements of the project. This was considered neither practical nor economical (Thavaraj et al., 2018) and therefore the use of concrete piles was dismissed for this project. Further discussion of the reasons regarding this reduction in resistance after ground improvement is given in the next sections.

On the other hand, results of CPT in the timber pile test section for spacings greater than 1.52 m (s/d=4.5) show a slight improvement at specific depths. In contrast, for spacings smaller than 1.22 m (s/d=3.6), the CPT results show an improvement until elevation -10 m,



(a) Concrete piles.



(b) Timber piles.

Figure 2. Comparison of pre and post-densification tip resistances from the compaction pilling program at pier S4.

generally meeting the required densification criteria. Therefore, timber compaction piles were proposed for densification of the soils under the bridge deck at pier S4.

3.3 *Production area*

Following the concrete and timber compaction test program at pier S4, timber compaction piles were proposed for the densification of the soils in the production area under the bridge deck. The production area is located to the east of pier S4 reaching a width of 10 m, length of 21 m and bottom elevation of -16 m. The piles used for the production area were like those used in the timber trial area with average tip diameter of 262 mm and head diameter of 378 mm. The piles were installed at 1.2 m spacing (s/d=3.8) in an equilateral pattern and were driven in three sections using two splices with single acting diesel hammers. A total of 179 piles were installed in the production area at Pier S4. Post production cone penetration tests were done, and results show that the required densification was generally achieved with the chosen pattern, spacing and installation procedure.

4 EVALUATION OF COMPACTION EFFECT IN TEST AREAS

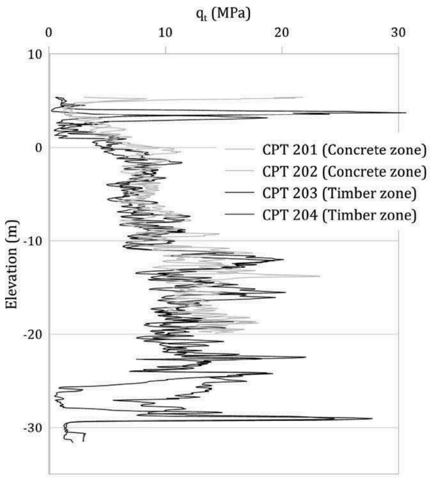
The characterization of the improvement is challenging due to the natural complexity and variability of soil deposits within a few meters. The soil profile was divided into two layers according to the material type, where layer 1 extends from 0 to 5 m below the ground level and consists of fill and natural overbank silt material, and the underlying layer 2 consists generally of sandy material.

Figure 3(a), shows the qt profiles obtained from tests in the two different test sections of the compaction test pile program. CPT 203 and CPT 204 were carried out before timber pile driving and CPT 201 and CPT 202 were performed before concrete compaction piles were driven. The four profiles are similar, follow the same trends and show the same interlayered deposits in the two areas. Following the approach by De Jong et al. (2016), the data were reprocessed to illustrate spatial variability by comparing the geometric averages of the two before densification soundings at the same depth in each site is shown in Figure 3(b). The geometric mean is calculated by taking the product of a series of numbers and raising it to the inverse of the length of the series, indicating the central tendency or typical value, in this case, of cone penetration resistance. Geometric averaging reduces the effects of extreme values on the calculated averages.

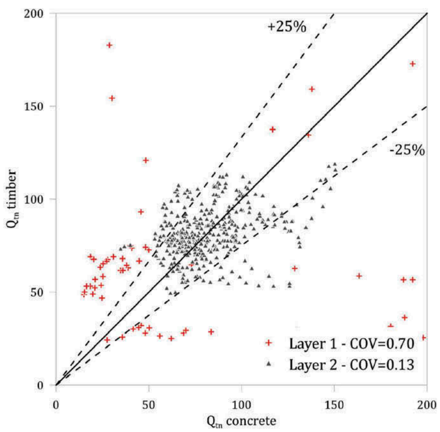
The data analysis indicates that variations of up to 70% in penetration resistance are expected in layer 1 and up to 15% for layer 2 across the two test areas. The extent of spatial variability that exists within the two test areas for layer 2, which underlies layer 1 and extends to approximately 30 m below the ground surface, is considered acceptable to compare the before and after ground improvement CPT results. However, due to the high variability of the results obtained for layer 1, this layer will not be further considered in the data analysis.

Once the cone penetration data were verified to be consistent at the test sites, the next step was to determine whether the soil can be improved or not through vibratory or impact methods.

Figure 4 presents two charts used to assess compactability of soil. Figure 4(a) illustrates the soils suitable for compaction on the normalized SBTn chart by Robertson (2009). Figure 4(b) shows zones of compactability on a CPT Soil Behaviour Type (SBT) chart based on non-normalized tip and friction values suggested by Eslami and Fellenius (1997; 2000). The initial cone penetration test data in the test area were geometrically averaged per meter depth. The plotted results in Figure 4 suggest that the Fraser River fine sand deposits should have been compactable.

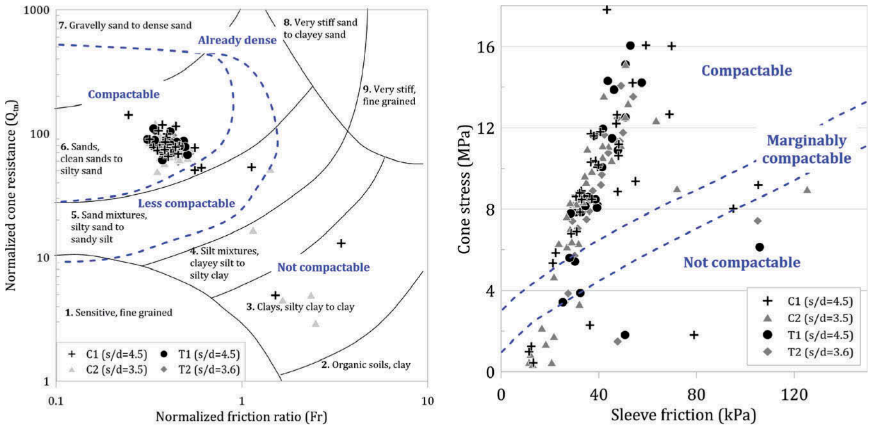


(a) Timber and concrete CPT results.



(b) Replotting pair data points at each depth.

Figure 3. Evaluation of spatial variability.



(a) Timber and concrete CPT results.

(b) Replotting pair data points at each depth.

Figure 4. Soil classification for assessment of compactable zones.

The database was examined for possible trends. Figure 5 shows the before and after normalized cone resistance plotted against normalized friction ratio. The tail and the head of the arrows in Figure 5 correspond to the before and after ground improvement data, respectively.

The data arrows for the concrete pile zone with wider spacing (C1) typically point straight down, showing that compaction caused a reduction of tip resistance and little change in the normalized friction ratio, suggesting an equivalent reduction in lateral stress. For the closer spacing zone (C2), the arrows point downwards and to the left, with a less dramatic drop in tip resistance and still a reduction in lateral stress.

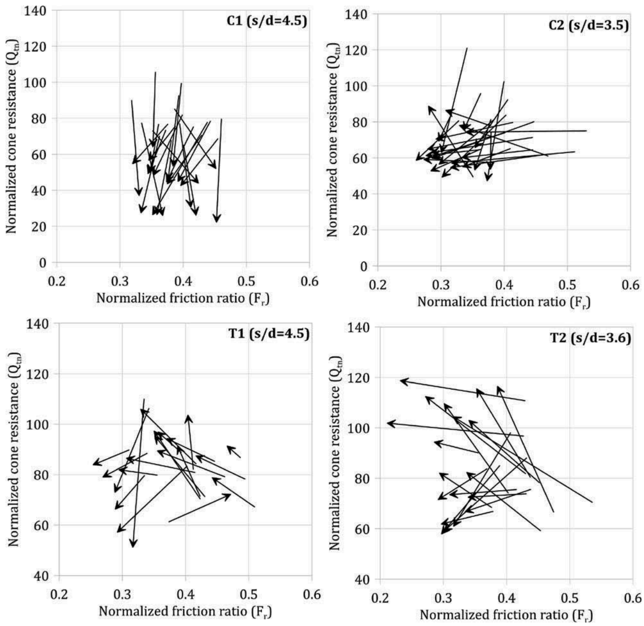


Figure 5. Evaluation of ground improvement based on normalized cone resistance and normalized friction ratio.

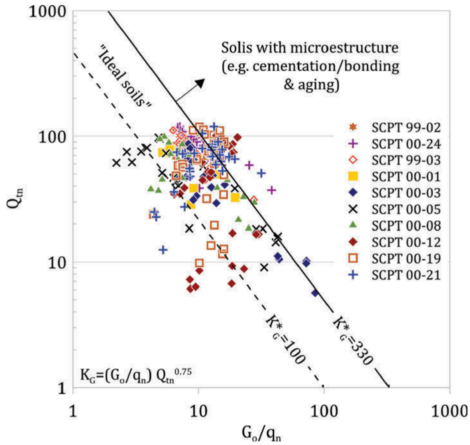


Figure 6. Correlation between normalized cone tip resistance and small strain shear modulus measured in seismic cone tests for the Mission Bridge site.

At the wider spacing in the tapered timber pile zone (T1) some arrows move upwards and some downwards but for the closer spacing (T2), the arrows point generally upwards and to the left, consistent with an increase in tip resistance and a comparatively lower increase in lateral stress on the friction sleeve.

Young, uncemented soils usually exhibit an increase in cone penetration resistance when compacted. Soils with some cementation or aging can show little change or even a drop in cone penetration resistance after ground improvement even after vertical settlements are observed. Robertson (2016) defines the latter type of material as "unusual soils" or as soils with microstructure. Eslaamizaad and Robertson (1996) and Schnaid (2009) suggested that seismic cone penetration tests (SCPT) can be helpful to identify soils with microstructure based on the small strain rigidity index (I_G), which is the link between G_o/q_t and Q_{tn}. Robertson (2016) suggested that soils with a normalized rigidity index (K_G) can be described as an ideal soil when $100>K_G>330$ or as an unusual soil when $K_G>330$.

Pre-densification seismic cone data from the Mission Bridge site are plotted in Figure 6. The data were averaged per meter according to depth increments used to calculate the shear wave velocity. The results show that a portion of the data corresponds to $K_G>330$ but most of the data points fall into the definition of an "ideal" material and so should have been compactable by compaction pilling.

5 SUMMARY AND CONCLUSIONS

As part of the seismic upgrade of the Mission Bridge, a test pile program was done at pier S4 and the results showed that timber piles were more effective in densifying the in situ material compared to straight cylindrical piles based on the before and after densification cone penetration tests. Consequently, tapered timber piles were selected for densifying part of the ground under the bridge deck at pier S4.

For this paper, the upper part of the soil profile was considered too variable for a detailed comparison of the effectiveness of cylindrical concrete and tapered timber piles. The sand layer extending from 5.0 m to around 30 m below the ground surface was considered suitable.

Standard approaches to assessing compactability indicated that this layer was likely compactable. Detailed examination of the CPT data indicated that both tip and friction appeared to be reduced by the installation of cylindrical concrete compaction piles installed at a practical spacing. Seismic CPT data did not suggest unusual (i.e. cemented or structured) soil conditions. Tapered piles were much more effective at increasing CPT tip resistance in the treated soil although the taper was not very large. The reasons for this difference requires further study.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of the Natural Science and Engineering Research Council of Canada (NSERC), the Ministry of Science and Technology from Costa Rica (MICITT) and the collaboration of Klohn Crippen Berger providing access to the data of the field tests done at the Mission Bridge project.

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