Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

Case study: Lessons learned from large scale pile driving in Waikeria, New Zealand

Étude de cas: leçons tirées du projet de fondations sur pieux à grande échelle à Waikeria, Nouvelle-Zélande

Idy Li, Michael Vinod and Jeff Hsi
EIC Activities, Australia

ABSTRACT: Construction of the Waikeria Prison Development Project in New Zealand involved the installation of over 3000 units of steel driven piles to support future prison buildings. A trial installation procedure was undertaken prior to production for the purposes of establishing and verifying driving requirements using drivability analyses. While piling delivery was compliant, early production end-of-drive sets were found to be significantly higher than those recorded during the trial procedure. This initially required up to 69% of the piles in some areas to be re-struck and additional testing to be undertaken to confirm the achieved pile capacity. In addition, the driving hammer energy efficiency recorded variations of up to 127%, casting doubt on the use of achieved set as a means of inferring pile capacities. This paper discusses the lessons learned on this project, including the importance of developing a trial procedure that closely matches production piling and the need to monitor hammer energy efficiency. These lessons will benefit those working with driven piles to to circumvent the issues encountered on this project.

RÉSUMÉ : La construction de la nouvelle prison de Waikeria en Nouvelle-Zélande a impliqué l'installation de plus de 3000 unités de pieux battus en acier pour soutenir les futurs bâtiments de la prison. Des essais ont été entrepris avant la production dans le but d'établir et de vérifier les spécifications proposées pour la mise en place des pieux. Au cours de la production, l'enfoncement des pieux s'est avéré significativement plus élevés que ceux enregistrés pendant les essais. Environ 69% des pieux ont nécessités un battage additionnel ainsi que des tests supplémentaires pour confirmer la capacité des pieux. De plus, l'efficacité énergétique du marteau moteur mesurée a affiché des variations allant jusqu'à 127%, jetant un doute sur les capacités des pieux et un doute sur les performances globales des fondations. Cet article examine les leçons apprises durant ce projet, y compris l'importance de développer une procédure d'essai qui représente étroitement les conditions sur sites et la nécessité de surveiller l'efficacité énergétique des marteaux. Ces leçons sont essentielles pour les ingénieurs travaillant sur des projets de pieux battus, pour apprécier les risques potentiels associés au battage de pieux et développer des méthodes pratiques pour résoudre certains des problèmes rencontrés sur ce projet.

KEYWORDS: Steel piles, pile driving, pile set-up; hammer energy efficiency.

1 INTRODUCTION

The Waikeria Prison Development Project is located 35 km south of Hamilton in the Otorohanga District, Waikato, New Zealand. The project involves the expansion of the existing facility, including 32 new prison buildings across the 27-hectare site. The new facility will accommodate approximately 500 people (CPB Contractors, 2018). The facility is due to be opened in 2022.

The project is being delivered under a PPP (Public-Private Partnership) contractual arrangement by Cornerstone Infrastructure Partners, comprising CIMIC Group companies Pacific Partnerships and CPB Contractors, and other consortium partners. CPB Contractors are responsible for the design and construction of the project. The prison will be operated by the Department of Corrections Ara Poutama Aotearoa.

The authors were engaged by CPB Contractors to work in partnership with the geotechnical consultant to advise on all ground and earthworks related issues, including the design of the foundation piles for the buildings.

2 GEOTECHNICAL CONDITIONS

The surface geology was divided into six main strata, as summarised in Table 1. The geological profile was relatively uniform across the site with the identified strata following a consistent layered sequence throughout, i.e. Unit 1 to Unit 6 arranged in order of increasing depth. Groundwater was recorded at approximately 2 – 3 m below the ground surface. Due to the loose and weak nature of the surficial strata and high groundwater table, Units 2, 3 and 4 were predicted to liquefy in the event of a 2,500-year return period design earthquake.

Table 1. Geological Profile

Unit Ref	Material Type and Consistency [1]	Depth to top of layer (m) [2]	CPT qc (MPa)	SPT N60 values
1	Ash mantle (St – Vst)	0.0 (0.0-2.8)	1.0-4.0	0-6
2	Silts/Clays & Sands (S – F, VL – L)	2.0 (0.1-5.0)	0.2-3.0	0-2
3	Silt, Sands & Gravels (St – Vst, MD – D)	6.6 (2.2-11.3)	4.0-20.0	15-50+
4	Silts/Clays & Sands (F, VL – L)	7.7 (3.2-17.1)	0.5-3.0	0-8
5	Sands & Silt (MD – D, Vst)	10.8 (6.6-15.6)	4.0-20.0	10-50
6	Sands & Silt (D – VD, H)	15.6 (9.4-24.4)	15.0+	50+

[1] Abbreviations for consistency defined as follows: S = soft, F = firm, St = stiff, Vst = very stiff, H = hard, VL = very loose, L = loose, MD = medium dense, D = dense and VD = very dense.
[2] Bracketed values indicate the range of depths; non-bracketed values relate to the average depth.

3 PILING DETAILS

3.1 *General*

Of the 32 new prison buildings, 27 were designed to be founded on piles supporting stiffened raft slabs. In total, over 3000 units of steel piles were required to cover the site.

A single steel section was selected for all 3000 piles, the properties of which are summarised below:

- Description: closed end circular hollow section
- Length: 13 - 24.8 m
- Diameter: 273 mm
- Wall thickness: 12.7 mm
- Yield strength: 350 MPa minimum

3.2 *Piling Specifications*

3.2.1 *Design Intent*

In addition to supporting the building structures by transferring the vertical loads down into competent ground, the piles were also required to maintain sufficient lateral capacity to support the structures in the event of seismic loading due to an earthquake and liquefaction of the upper strata.

3.2.2 *Drivability Assessment*

To establish driving requirements for construction, drivability analyses were undertaken using GRLWEAP software (Pile Dynamics Inc., 2010) to simulate the expected ground conditions and energy delivered by the preferred piling rig, Junttan HHK7s PM25 and a 7-tonne hydraulic hammer. The drivability analyses predicted a specification of 9 mm / blow at the end-of-drive (EOD) to attain the desired ultimate capacity, using a hammer drop height (stroke) of 600mm.

3.2.3 *Trial Procedure*

In order to verify the drivability requirements, a trial procedure was undertaken ahead of the main production pile installation using a total of 22 test piles spread amongst the proposed locations of the piled buildings. The trial was also intended to establish additional requirements for the remaining 3000 production piles and to complete the bulk of the pile testing requirements (see Section 3.2.4) ahead of the project schedule.

Trial piles were installed using the piling rig Junttan HHK-7S PM 25 and a 7-tonne hammer. Dynamic testing using a pile driving analyser (PDA) and Case Pile Wave Analysis Program (CAPWAP) analysis (Pile Dynamics Inc., 2014) was undertaken on all trial piles at the following stages of installation, (a) before end-of-drive (EOD), (b) at EOD and (c) at re-strike (2 – 10 days after completion of pile installation). The key findings of the trial procedure are summarised in Table 2. Note that the values within each column are independent of each other, i.e. the pile with the lowest achieved EOD set does not correspond to the pile with the smallest EOD PDA capacity.

Table 2. Trial Procedure Summary

Units	Achieved EOD set	Driving time	EOD PDA Capacity	Re-strike PDA Capacity
	mm / blow	minutes	kN	kN
Minimum	0.1	17	1650	1760
Average	2.9	39	2079	2662
Maximum	10.4	81	2855	2935

3.2.4 *Final Design Requirements*

Considering the need to found the piles within competent strata to support the building loads and maintain sufficient lateral pile capacity in the event of an earthquake and liquefaction, the project team developed a set of driving requirements that would facilitate the confirmation of the desired vertical pile capacity as well as a minimum penetration into reliable stratum (Units 5 and 6). The project team developed the requirements using the results of the trial procedure and corresponding ground strata noted within nearby borehole records. The criteria below have been paraphrased from the original requirements.

General requirements

1. Piling conditions require use of 7-tonne hydraulic hammer and drop height of 600mm.
2. Attainment of minimum pile length stipulated for each building. (Specified minimum pile lengths ranged between 14 – 20 m below ground level.)

Set requirements

3. Achieve set < 9 mm / blow at EOD. The project team concluded from the trial procedure that 9 mm / blow EOD was consistent with attainment of the desired pile capacity.
4. Penetration of 3 m into reliable Unit 5 or Unit 6 material – demonstrated through achieving ≥ 10 blows per 250 mm of penetration (equating to set of 25mm / blow) for a length of ≥ 3m
5. Minimum of 25% piles (for entire project) shall be re-driven after a minimum of 48 hours following EOD. Piles shall be selected by a geotechnical engineer and must achieve a minimum of re-strike set < 3 mm per blow.

Testing requirements

6. A total of 7.5% (including the already tested 22 trial piles) of all project piles shall be tested by PDA. Of the piles tested by PDA, a minimum of 25% shall be analysed using CAPWAP

4 CONSTRUCTION ISSUES

As installation of the production piles commenced, a large proportion of piles for each building, all of which had been driven to the maximum required depth, were not achieving requirements 3 and 4 (noted in Section 3.2.4) above, pertaining to the limiting set criteria. It was particularly concerning that the achieved EOD sets were significantly higher than 9 mm / blow – generally recording in excess of 15 mm / blow up to a maximum of 62 mm / blow.

In response to these non-conformances, the project team re-struck on average 29% of piles and conducted additional PDA tests and CAPWAP analyses to confirm the capacity of the non-conforming piles. Despite the initial EOD exceeding the 9 mm / blow requirement by such a large margin, all of the piles selected for re-strike achieved the criteria of < 3 mm / blow and all the PDA / CAPWAP results indicated the necessary pile capacity had been achieved for all the buildings. One building was an exception, which initially registered non-conforming PDA / CAPWAP results due to unexpected ground conditions, this was later remedied with longer piles. The recorded set results for a typical building with non-conforming EOD sets and low re-strike sets are presented in Figure 1. All piles within this building had achieved the maximum embedment depth during the initial drive.

Additional PDA and CAPWAP analyses were requested as it had been identified that the driving energy transmitted to the piles was inconsistent. The energy during PDA testing recorded extremes of 39% to 166% efficiency on two separate occasions. As such, the project team stated that the achieved driving sets could not be used as reasonable means of confirming the inferred pile capacity.

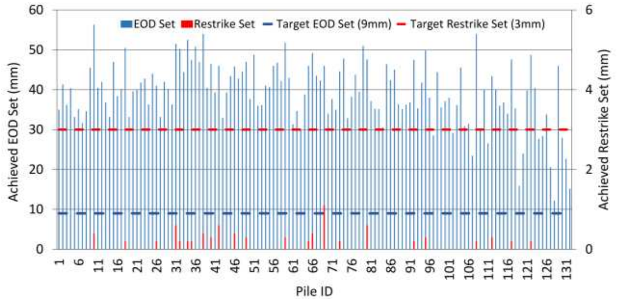

Figure 1. Typical building (Visual, Audio Visual Link and Parole Board, VIS) pile summary with high EOD set and low re-strike set. Maximum embedment depth achieved during initial drive with average energy efficiency >90%.

The additional re-strikes and PDA / CAPWAP testing challenged the tight project timeframe due to the unexpected redirection of piling rigs for re-striking. Further, the project team experienced long wait-times for PDA testing and CAPWAP analyses, due to the limited availability of the independent PDA testing authority.

5 BACKGROUND AND SOLUTIONS TO CONSTRUCTION ISSUES

5.1 *Transferred Hammer Energy Efficiency*

5.1.1 *Definition*

The transferred hammer energy efficiency refers to the ratio between the energy transferred to the pile to the potential energy of the hammer based on the notional hammer stroke, i.e. the height from which the hammer is dropped. This ratio is a critical factor to determine the amount of energy delivered into the pile as it is struck.

5.1.2 *Site Observations*

The hammer energy efficiency assumed in the drivability calculations (GRLWEAP, refer Section 3.2.2) was 87% based on ENTHRU values. However, energy measurements of production piles from PDA testing indicated the median energy efficiency was below 70% in one testing period, and the range of recorded energy efficiencies varied by up to 127% (i.e. between 39% to 166%) during the first two months of piling. Refer to Figure 2 for the hammer energy efficiencies recorded throughout the course of the project for piling rig Junttan HHK7s PM25.

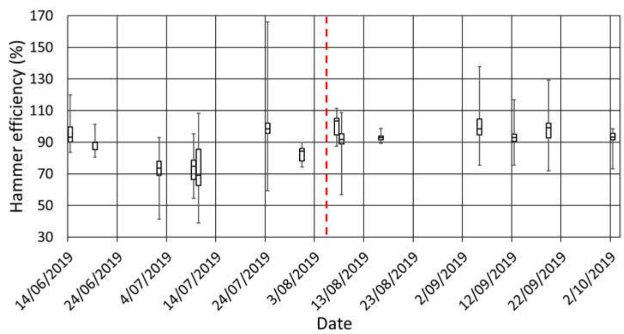

Figure 2. Hammer energy efficiency for Junttan HHK7s PM25 with 7-tonne hammer over time. Dashed red line indicates date of implementation of PVC tube on rig mast to facilitate confirmation of hammer drop height. The gradations on each box and whisker plot relate to the minimum, lower quartile, median, upper quartile and maximum test results recorded during each period of testing.

This energy efficiency variation raised doubts around the viability of using set-based criteria (such as requirements 3, 4 and 5 noted in Section 3.2.4) to inform the achieved pile capacity, as the accuracy of these criteria are fundamentally dependent on the consistency of the transmitted energy.

Upon discussion with the project team we were advised that the drop height of the hammer could not be controlled via any mechanism within the rig operator's compartment. Drop heights were controlled based on the operator's visual gauge of the raised hammer height only.

5.1.3 *Proposed Solution*

A physical marker comprising a 600 mm PVC tube was attached to the rig mast to provide a visual aid for the rig operator to ascertain the hammer drop height, as shown in Figure 3. Once this mechanism was put into place, the median hammer energy efficiency recorded in excess of 92% consistently in the following weeks, compared with less than 70% in the weeks prior, as shown in Figure 2. The range of energy variability decreased from 127% to 81% (i.e. ranging between 57% to 138%), due to the relative consistency in stroke that was being achieved with the PVC tube in place. The dotted red line in Figure 2 indicates the date when the PVC tube was installed in early August 2019.

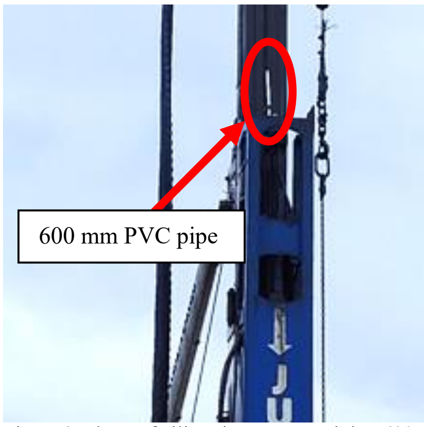

Figure 3. Photo of piling rig mast containing 600mm plastic pipe to allow visual verification of drop height of hammer.

Despite the increase in energy efficiency and consistency, the team mitigated the dependency on the achieved set by ensuring that most (if not all) the piles for the majority of the buildings were installed to the maximum target embedment depth. The project team also maintained additional re-strike and PDA / CAPWAP tests above the specified testing rate in light of the energy variability which was still prevalent. Selection of piles for testing involved reviewing the achieved sets within a localised zone, and those which recorded the highest sets were selected for testing. All the piles consistently achieved the re-strike criteria (refer requirement 5 in Section 3.2.4) and desired ultimate capacity.

5.1.4 *Literature Review*

According to Seidel (2015, 2015a), large variations in driving energy in excess of 30% are not unusual, even within projects that are well-controlled using a single model of hydraulic hammer and rig, and constant hammer stroke. Based on Seidel's (2015, 2015a) experience, variations in energy delivery have been described as varying randomly, significantly and unsystematically. Due to such variabilities, doubt is cast over the validity of commonly used methods to infer pile capacities during pile driving, such as achieved set, use of wave equations and dynamic formula – all of which are fundamentally dependent on the transferred energy being constant.

Thus, without capturing these variations in the applied piling criteria, the inferred pile capacity will be erroneous and unreliable. To address such inconsistencies in driving energies and risks inherent to the use of conventional pile driving criteria, Seidel (2015, 2015a) refers to the use of non-contact monitoring using a Pile Driving Monitor, PDM, (in conjunction with PDA testing), which has the ability to monitor the velocity of the pile as it is driven and consequently report on the energy delivered to the pile in real-time.

5.2 *EOD Set Discrepancy*

5.2.1 *Observations and Postulations*

Once the PVC tube had been installed and the median energy efficiency was elevated in excess of 92%, the achieved set values were then considered to be a relatively more reliable indicator of pile performance. However, the issue of excessive EOD sets remained unsolved. The authors undertook a detailed interrogation of the drivability results, and the trial procedure conditions versus production conditions. The authors noted no discernable differences between the conditions for the trial procedure and production piles. The following conditions were almost identical: piling rigs, hammers, stroke, installation crew, pile types, and locations / geology.

However, upon detailed review, the driving times during the trial procedure were identified to be longer than the production piles, as shown in Table 3. On average, trial piles were installed in 39 minutes versus 13 minutes for the production piles. Despite the difference being only a matter of minutes, the authors postulated that the increase in driving time had allowed the ground to achieve greater set-up during the trial procedure, thereby allowing the effective stress of the ground to increase, resulting in smaller penetrations per hammer blow. Further, it was clear from the EOD and re-strike capacities recorded from PDA tests undertaken during the trial procedure (refer Table 2), that set-up phenomenon (as opposed to relaxation) was evident after a period of 2 - 10 days. A selection of the achieved EOD sets for trial piles and their neighbouring production piles is provided in Table 3.

Table 3. Comparison of EOD sets and driving times from trial piles versus neighbouring production piles (mm / blow)

Trial Pile ID	EOD set (mm) Trial	EOD set (mm) Production	Driving times (mins) Trial	Driving times (mins) Production
TP3	2.4	6 (0.3-27)	50	15 (9-24)
TP5	0.4	16 (10-27)	36	9 (7-11)
TP17	1.5	9 (4-15)	45	9 (7-10)

5.2.2 *Literature Review*

Pile set-up refers to the increase in capacity of driven piles over time mainly due to dissipation of pore water pressures and the associated increase in effective stress. Komurka et al. (2003) categorises pile set-up into three phases in log time (1) non-linear rate of excess pore water dissipation with time, (2) linear excess pore water pressure dissipation with time and (3) ongoing process of pile capacity with time at a lower rate as shown in Figure 4.

Factors found to affect pile set-up include geological conditions, groundwater location and pile type. Piles installed in sand with a high groundwater table have been shown to dissipate quickly in a matter of minutes (Bullock, 1999) resulting in large set-up in the short term (Phase 1); some set-up during logarithmically linear stage (Phase 2); and another large portion during ageing (Phase 3) (Axelsson, 2002). Piles installed within clay would dissipate slowly during Phase 1, with the majority of set-up occurring during the log-linear stage (Phase 2) and little to no set-up during Phase 3 (Komurka et al., 2003). Set-up rate has been shown to decrease as pile size increases (Camp & Parmar, 1999) and wooden piles set-up faster than steel or concrete piles (Bjerrum et al., 1958).

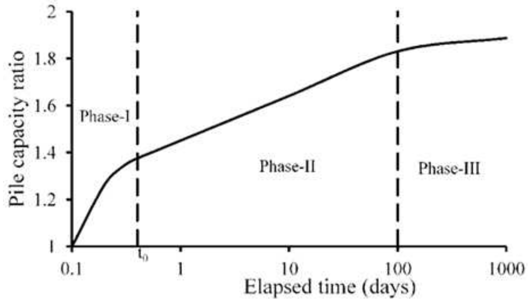

Figure 4. Different phases of set-up (adapted from Komurka et al., 2003)

5.2.3 *Verification of Set-Up*

To verify this postulation, the authors requested two piles to be driven adjacent to each other on site at several locations, each of identical length and size, but varying in installation rate. At each of the test locations, the piles driven at a slower rate achieved significantly smaller sets. At one location, shown in Figure 5, Pile A was installed over a period of 45 minutes and Pile B within 20 minutes. The piles were located 0.6 m laterally offset from each other. The achieved EOD was <1mm and 19 mm respectively.

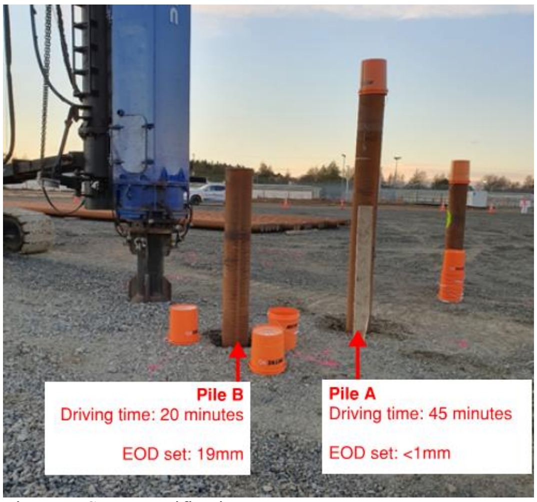

Figure 5. Set-up verification test

To investigate the relationship between installation rate and achieved EOD set, a plot of the embedment per driving time (i.e. installation rate) versus EOD set for each pile was developed, as shown in Figure 6. All available pile data from the Junttan HHK7s PM25 piling rig including trial piles and production piles gathered during periods of relative consistent hammer energy efficiency were included. Figure 6 depicts a generally linear trend which indicates that higher rates of installation were associated with higher EOD sets, i.e. slower rates of installation achieved lower EOD sets. A significant number of "non-conformances" are apparent based on the large number of EOD set results plotting in excess of piling requirement 3, i.e. 9 mm / blow. Using the data set below, the average installation rate for trial piles and production piles was calculated to be 0.5 m / min and 2.35 m / min respectively.

From these experiments and graphical data, the authors concluded that the large EOD sets achieved during production versus the trial procedure was due to the accelerated rate of production installation.

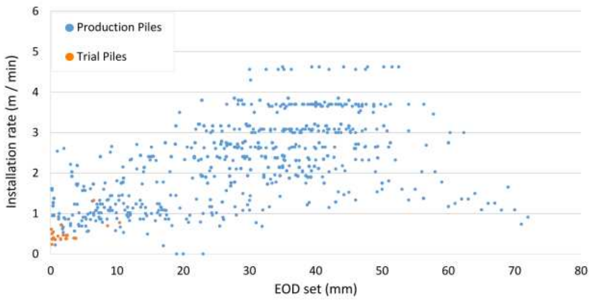

Figure 6. Installation rate versus EOD set

It was later identified that the prolonged installation time for the trial piles was due to the installation of strain gauges and PDA measurements carried out prior to EOD and at EOD. In the few minutes that these installations and testing procedures took place, sufficient set-up had occurred to allow the effective stress to increase substantially. For production piles, pre-EOD PDA tests were not undertaken, and only a very limited percentage had PDA tests at EOD, so installation rates were comparatively faster. Further, as construction proceeded, the efficiency of the construction crew improved, further reducing the installation rates

5.2.4 *Proposed Solution*

Despite the production piles consistently exceeding the EOD set 9 mm / blow (requirement 3) and repeated non-conformance of requirement 4, all the additional re-strike tests and PDA / CAPWAP tests proved the piles had achieved the desired ultimate capacity. Accordingly, the authors collaborated with the geotechnical designers to develop a new acceptance requirement that took into consideration the production installation rates, being a maximum set < 16 mm / blow at EOD. This replaced original requirements 3 and 4. Once the new requirement was implemented, the approval rates for the piles improved and rates of re-strike and additional PDA / CAPWAP were reduced. Again, all the piles consistently achieved the re-strike criteria (refer requirement 5 in Section 3.2.4) and desired ultimate capacity. The construction schedule for the pile-supported buildings and structures was able to recover to its original program.

5.2.5 *Geological Influence of Set-up*

Whilst it was clear that set-up effects were the primary contributor to the variation in achieved sets, an attempt was made to identify the geological stratum responsible for the set-up condition. The authors collated trial pile information together with the production piles in its vicinity and plotted the achieved blow count (inverse of set in units of blows per metre) versus depth. See Figure 7 below. Each plot contains records of one trial pile (TP), plus eight production piles located within 3 m of its vicinity. Adjacent to each graph is a summary of the increase in shaft resistance along the trial piles gained between the EOD and re-strike extracted from CAPWAP results. A summary of the expected ground stratum has been extracted from the nearest available borehole and overlain onto each figure. Note that the groundwater level is located approximately 2 - 3 m below the ground level.

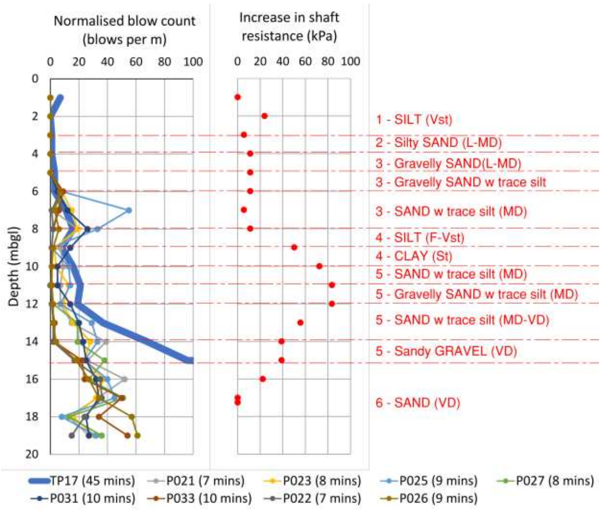

Figure 7(a): TP17. Re-strike test undertaken five days after EOD

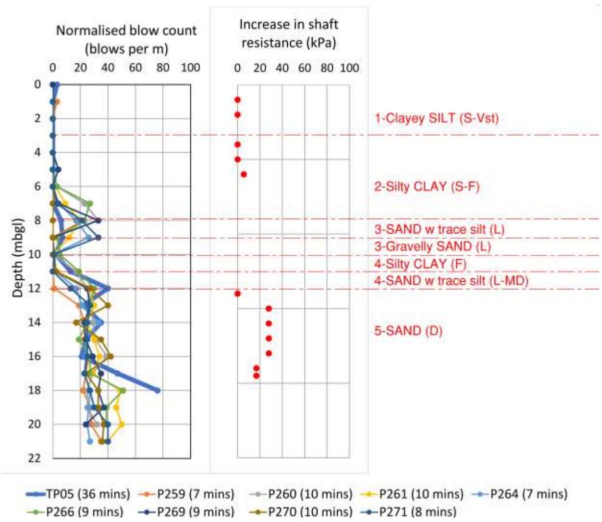

Figure 7(b): TP05. Re-strike test undertaken eight days after EOD

Figure 7. Achieved set versus depth for trial piles and adjacent production piles. Increase in shaft resistance obtained from CAPWAP results on trial piles at EOD and re-strike

In Figure 7(a) the set values begin to deviate between the trial piles and production piles at a depth of 10 m below ground level associated with Unit 5, recorded as medium dense coarse-grained materials – sand with trace silt. The greatest increase in shaft friction recorded in the CAPWAP records (over five days) also commences at this depth. The materials recorded below this level are of a similar description and density, predominantly medium dense to very dense coarse-grained sands and gravels with silt present as a minor / trace fraction. Note the installation time for the trial pile (TP17) is 45 minutes versus 7 – 10 minutes for the production piles. The significantly higher blow counts per metre (inverse of set) achieved in the trial pile compared with the production piles suggest that these geological units may be the primary materials responsible for the set-up effects.

Conversely, large blow count discrepancies between the trial pile and production piles were *not* observed in Figure 7(b). Trial pile TP05 and surrounding production piles had similar deviations between the installation times as per TP17 in Figure 7(a), but the recorded geologies were different to Figure 7(a). In Figure 7(b) the profile is dominated by purely fine-grained (Unit 1 and 2, clayey silt or silty clay) or purely coarse-grained material (Unit 5, dense sand). The purely coarse-grained or purely fine-grained materials did not appear to generate the same degree of set-up effects, evidenced from the smaller increases in shaft resistance compared with TP17, and relative similarities between the achieved trial pile and production pile sets.

Based on these findings, the authors concluded that the geologies responsible for rapid set-up were likely to be the medium dense to dense coarse-grained sand / gravel layers with silts as the minor fraction, which dominate the geological profile in Figure 7(a). The authors postulate that the presence of high groundwater levels allowed increases in pore pressure to develop during rapid driving of the production piles, and the silts / finer grained sand allowed the pore pressure to elevate. The higher rate of installation generated higher pore pressures and thus greater reduction in effective stress, allowing the achieved sets to increase, i.e. blow counts to reduce. Subsequently, the presence of sands and gravels allowed the pore pressure to dissipate rapidly, within a matter of minutes. This mixed geology covers the two extreme geological conditions and set-up responses for the coarse-grained (sands and gravels) and fine-grained soils (clays and silts) mentioned in Komurka et al., 2003 (summarised in Section 5.2.2).

The density of the strata is critical, as the stark difference in set between trial piles and production piles was only observed in medium dense to very dense material in the samples shown below 10 m depth in Figure 7(a). Conversely, refer to Figure 7(a) at depths of 3 – 8 m below ground level, where loose sand with trace silt did not present any significant differences between the trial pile and production pile sets. It is likely that with grains packed at higher densities the pore pressure dissipates slower compared with loose sands, due to the smaller voids allowing the pore pressure to dissipate. Thus, densely packed coarse grains with a small fraction of silt are postulated to have generated higher increases in pore pressures due to rapid driving, thereby generating higher reductions in effective stress and lower blow counts per metre. Thereafter, set-up occurs fairly rapidly due to the presence of sands and gravels.

It is likely that the increase in blow count observed in the trial piles (below approximately 12mbgl and 16mbgl for TP17 and TP05 respectively) may be partially attributed to the temporary stoppage of pile driving for the installation of PDA strain gauges at the identified levels. However, it is the authors' opinion that the presence of medium dense to dense coarse-grained sand / gravel layers with silts as the minor fraction would have exacerbated the set-up effects compared with other geologies.

6 CONCLUSIONS AND DISCUSSION

The key lessons learned from the pile driving works at the project include the following:

1. Undertaking trial pile installations prior to production piling are essential for the success of any piling works and should be carried out under the closest possible conditions to production piling. Particular attention should be paid to ensure the rates of pile installation (including interim stoppages) during production are replicated during the trials, as this can have a significant impact on achieved set and re-strike values.
2. Hammer energy efficiency should be closely monitored during pile driving to ensure it remains constant throughout the works. Some piling rigs do not contain mechanisms to allow the operator to control hammer drop heights, resulting in variable driving energies transmitted into the piles. Visual aids can be attached to piling rigs to ensure a more consistent hammer drop height.
3. Large variations in driving energy in excess of 30% are common, even in well-controlled environments, with uniform rigs, hammers and drop heights. Thus, commonly used methods to confirm pile acceptance such as EOD set and dynamic formula may prove erroneous and unreliable due to the inconsistency of delivered driving energies. Non-contact monitoring with a Pile Driving Monitor, PDM, (in conjunction with PDA testing), can be used to monitor the velocity of the pile as it is driven and consequently report on the energy delivered to the pile in real-time (Seidel 2015, 2015a).
4. Predictions of pile drivability using wave equation software such as GRLWEAP should be used in conjunction with pre-production trials to ascertain reliable estimates of drivability / target set criteria. While drivability software can provide practitioners with a prediction of the driving conditions, these are estimates only and can only reflect reality if the appropriate input factors relating to pore pressure build-up, and rates of dissipation are entered accurately.
5. The authors consider certain geological conditions and set-up phenomena were responsible for the considerable differences in set between the trial piles and production piles – namely high groundwater levels and densely packed coarse grains with a small fraction of silt. These materials are postulated to have generated higher increases in pore pressures due to rapid driving, thereby generating higher reductions in effective stress and lower blow counts per metre, i.e. greater sets. The presence of sands and gravels would have allowed set-up to occur fairly rapidly thereafter. In the event similar ground conditions are encountered in future, the authors would suggest that particular care is paid to establishing the set criteria and multiple trials are undertaken pre-production to establish the rates of set-up that can be achieved.

7 ACKNOWLEDGEMENTS

The authors wish to thank CIMIC Group clients and the CPB Contractors construction team at the Waikeria Prison Development Project for their efforts in delivering this project, and their approval to have the content of this paper published.

8 REFERENCES

Axelsson, Gary. (2002). "A Conceptual Model of Pile Set-up for Driven Piles in Non-cohesive Soil." *Deep Foundations 2002: An International Perspective on Teory, Design, Construction, and Performance*, Orlando, Florida, 64–79

Bjerrum, L., Hansen, and Sevaldson (1958). Geotechnical Investigations for a Quay Structure in Ilorton. *Norwegian Geotech. Publ. No.* 28, Oslo.

Bullock, Paul Joseph (1999). Pile Friction Freeze: A Field and Laboratory Study, Volume 1, *Ph.D. Dissertation*, University of Florida.

Camp III, W.M., and Parmar, H.S. (1999). Characterization of Pile Capacity with Time in the Cooper Marl: A Study of the Applicability of a Past Approach To Predict Long-Term Pile Capacity, *Emre, TRB*, pp. 1-19.

CPB Contractors (2018). NZ$750M prison PPP. [online] Available at: https://www.cpbcon.com.au/en/news-and-media/2018/nz$750-million-prison-ppp [Accessed 2 Nov. 2020]

Komurka, Van E., Alan B. Wagner, and Tuncer B. Edil. (2003). Estimating Soil/Pile Set-up (No. Report No. 03-05). *Wisconsin Highway Research Program*.

Pile Dynamics Inc. (2010). GRLWEAP. Ohio, USA.

Pile Dynamics Inc. (2014). CAPWAP (Case Pile Wave Analysis Program). Ohio, USA.

Seidel, J.P. (2015). Overview of The Role of Testing and Monitoring in the Verification of Driven Pile Foundations. *12th Australia New Zealand Conference on Geomechanics*.

Seidel, J.P. (2015a). Enhanced Use of Dynamic Pile Testing in Foundation Engineering. *12th Australia New Zealand Conference on Geomechanics*.