The use of remote high strain dynamic testing and high frequency displacement monitoring to improve safety and quality – case study LPC admin and operations building

R Damen
Brian Perry Civil, Auckland, NZ
ronaldd@fcc.co.nz (Corresponding author)

M D Larisch
Brian Perry Civil, Auckland, NZ
martinla@fcc.co.nz

Keywords: health and safety, high strain dynamic testing, PDA, driven piles

ABSTRACT

The foundation of the Administration and Operations Building of Lyttelton Port of Christchurch (LPC) required the installation of 81 driven steel piles, of which 8 were tested using high strain dynamic testing (PDA). The majority of these high strain dynamic tests were conducted remotely, with the testing engineer operating from Auckland. Remote testing reduced turnaround time on the testing, enhanced quality of data collection and reduced safety hazards for the testing engineer.

Measurements of driving set and temporary compression were conducted using high frequency displacement monitoring. In contrast to the traditional manual set card, measurements could be taken from outside the exclusion zone, which provided significant reduction of hazards to the site crew. Due to the high frequency of the monitoring, the quality of the measurements and reporting was also greatly improved.

1 BACKGROUND

The foundation of the new Administration and Operations Building for Lyttelton Port of Christchurch (LPC) comprises 81 driven steel H-piles (76 No. 310UC158 and 5 No. 400HCC252, all steel grade 300SO), which were installed by Brian Perry Civil (BPC). The design for the foundation was done by Golder Associates (hereafter referred to as the Engineer). The building itself consists of 3 stories, with a footprint of approximately 1800 m².

Geotechnical investigation was limited, with 2 CPTs and 2 boreholes completed. Shear wave velocity tests were conducted in 2 locations. The site is located in a land reclamation site, which was previously used for timber storage. Reclamation fill is present from ground level to a depth of approximately 9 to 18 m below ground level, underlain by 7 to 12 m of estuarine deposits and loess colluvium. The fill was expected to comprise of sandy and silty gravel with the presence of cobbles and boulders. Bedrock consists of weathered to fresh basalt of the Port Hills Volcanics (Dismuke, 2016). Piles were to be founded in the weathered bedrock. The uncontrolled fill layer overlying the site was of particular concern with regards to the pile driving process. In order to limit the risk of premature pile refusal and localised pile damage due to obstructions, all 81 pile locations were pre-augered to a depth of 14 to 18 m using a Soilmec SR-30 with a 450 mm CFA auger. During the pre-augering, no spoil was removed from the pile locations.

Piles were pitched and vibrated to refusal using an ICE 23RF resonance free vibratory hammer and subsequently impact driven to target levels using a BSP HH9 hydraulic hammer.
2 HIGH STRAIN DYNAMIC TESTING

High strain dynamic testing is a pile testing procedure that uses strain gauges and accelerometers attached to the pile to evaluate force and velocity of a driven pile. The test is commonly conducted using an impact pile driving hammer. The impact causes a stress wave that travels down the pile, moving the pile relative to the surrounding soil. The mobilised soil resistance at the shaft of the pile reflects compression waves back up the pile. Depending on the soil type at the pile toe, a tension wave or compression wave is reflected upwards. The cumulative effect is an upward travelling force wave that can be inferred from the force and velocity, and which is indicative of the total dynamic resistance of the pile. Additionally, the measurements provide information on the total amount of energy transferred into the pile, which, combined with information on the potential energy of the hammer, can be translated into hammer efficiency. Also, maximum average driving stresses at the location of the gauges can be calculated and large defects in the pile shaft may be identified.

Proprietary testing systems include the Pile Driving Analyzer (PDA) by Pile Dynamics and the PDR by Allnamics.

The inferred resistance obtained from the measurements includes the dynamic resistance of the pile-soil interface. In order to infer the geotechnical ultimate strength ($R_{ug}$) against static loading, this dynamic component must be eliminated. A field estimate can be made by applying an overall damping factor, such as the Case damping factor $J_c$ (Hussein & Likins, 1991). Further accuracy is obtained by conducting a process called signal matching, in which the measured signal is compared to a signal that is generated by a wave equation model. An iterative process is applied to adapt the model to match the measured signal to an acceptable level. There is no unique solution, and non-credible soil-pile models may result in a good match quality. Therefore, it is essential that the signal matching process is conducted by a skilled and experienced engineer, and is based on a credible soil model (Rausche et al., 2008; Seidel, 2015). Proprietary software to conduct this signal matching process includes CAPWAP by Pile Dynamics and AllWave-DLT by Allnamics.

In the LPC project, high strain dynamic testing was specified by the Engineer as a means of quality assurance for the pile foundation. 10% testing (8 No. piles) was required, with test pile locations specified by the Engineer. Testing was conducted using an 8G PDA, with 2 piezo-electric strain gauges and 2 accelerometers per pile. Signal matching was conducted by a third party using CAPWAP.

The objective of the test was to verify that the piles had obtained the required geotechnical ultimate strength ($R_{ug}$) and were embedded at least 0.5 m into a competent bearing strata (i.e. weathered rock). The required minimum $R_{ug}$ for the 310UC158 piles was 2,100 kN and required $R_{ug}$ for the 400HCC252 piles was 5,000 kN. This was based on a geotechnical reduction factor ($\phi_g$) of 0.48 in accordance with AS2159-2009. Figure 1 summarises the ultimate geotechnical strength obtained from signal matching in relation to the driving sets.
In addition to determining the ultimate geotechnical strength of the piles, the high strain dynamic testing was used by the contractor to also monitor driving stresses and verify pile integrity for the full duration of impact driving of the first pile (pile P81). As can be seen in Figure 2, the driving stresses were well below the allowed 90% of the steel grade (i.e. 270 MPa), in accordance with AS2159:2009.

Figure 1: Geotechnical ultimate strength from signal matching vs average driving set

Figure 2: Average Compressive Stress (CSX) vs Blow Number pile P81
3 REMOTE TESTING

High strain dynamic testing requires a skilled and experienced engineer to conduct and monitor the test and subsequently conduct the signal matching process (Rausche et al., 2008).

Traditionally, a skilled testing engineer would mobilise to the construction site for each test, which results in potential down time of the piling operation on site, inefficient use of the testing engineer’s time and higher cost. Alternatively, tests could be bundled to reduce the number of site visits by the testing engineer. However, this may not align with the optimum piling sequence, as test piles are generally geographically spread over the site.

The 8G PDA system that is used by BPC has remote capability, which allows remote access to the system. This capability was utilised by BPC for the first time in New Zealand on this project.

During driving of the first pile, the testing engineer mobilised to site and trained the site engineer to correctly prepare the pile, connect gauges and set up the system. The first test was conducted by the testing engineer onsite. All following tests were conducted remotely, with the Auckland-based testing engineer accessing the PDA system through an internet connection.

Pile testing was conducted satisfactorily using this method. Most notably, the turnaround time for testing could be reduced significantly. Generally, at the start of the week the site engineer and testing engineer discussed over the phone which selected test piles were due for testing. Testing windows were agreed upon, ensuring the testing engineer’s availability and were narrowed down on the actual test day. Actual pile testing took less than one hour on average to conduct.

This approach provided significant flexibility to the site crew to adapt the testing schedule to the piling operation on site. For example, pile tests could be easily rescheduled when the installation of test piles was delayed due to breakdown of hired plant.

4 HIGH FREQUENCY DISPLACEMENT MONITORING

A key input parameter to driven pile verification is the driving set, or permanent displacement per hammer blow. Furthermore, the temporary compression is generally recorded, which is indicative of the dynamic effects in the pile and is used in dynamic formulae, such as the Hiley formula (Hiley, 1930; Auckland Structural Group, 2002).

Traditionally, the only method to record the temporary compression, was by means of a manual set card, in which a pencil or chalk is physically held by person to the pile (or to a paper attached to the pile) during pile driving. Often an inclined spirit level is used to provide a more or less stable reference level. The result can then be measured. This method is commonly applied for 10 impact blows, and results are subsequently averaged. Figure 3 shows an example of a manual set card.
The obvious disadvantage of this method is the high safety risk, since it requires a person to be in close proximity to the pile during the driving process. The method requires significant skill and experience of the person recording and is therefore highly operator dependent, which potentially impacts the quality of the measurements. Temporary ground displacements around the pile may also affect the measurement.

High frequency displacement monitoring was developed to enhance the quality of set and temporary compression measurements, using optical sensors and high power light emitting diodes (LED) in combination with reflectors on the pile. The Pile Driving Monitor (PDM), developed by Advanced Foundation Technologies, was used on this project. The PDM has a sampling rate of 4,000 Hz, and can be used at an offset distance of 6 to 20 m from the pile (Advanced Foundation Technologies, 2015).

BPC used the PDM (Model G2) to replace manual set cards on all piles of this project. The main reason to use the PDM on this project was the obvious benefit to occupational safety. The device enabled the site engineer to measure set and temporary compression, whilst being well outside the exclusion zone (see Figure 4).
Additional benefits are the increased accuracy of the measurements and the operator independency of the method. An example of the PDM results as reported to the client is shown in Figure 5.

PDM training was provided by the testing engineer to the site engineer, in addition to PDA training. The site engineer was able to conduct all PDM tests, with minor remote support from the testing engineer.

Lessons learned included avoiding exposure to heat, as the PDM and accompanying tablet quickly overheated when exposed to sunlight for longer durations (30 minutes). Furthermore, enabling a clear line of vision for the PDM to the pile proved challenging as piling proceeded and the site became more congested. Offset distance is a key input parameter and results are sensitive to this input. Therefore, three measurements were made of offset distance using a laser distance gauge (Ryobi RLM30).

5 CONCLUSION

High strain dynamic testing demonstrated that all piles were driven to the required ultimate geotechnical strength ($R_{ug}$). Driving stresses were found to be well within the limits specified by AS2159:2009, and no indication of overstressing or pile damage was observed.

The application of remote testing provided significant flexibility to adapt pile testing to the piling operations. Additionally, turnaround times were reduced.

The replacement of manual set cards by high frequency displacement monitoring led to health and safety benefits, in conjunction with higher quality and operator independent set and temporary compression records.
REFERENCES


Hiley, A. (1930) Pile-driving calculations with notes on driving forces, and ground resistance. *The Journal of the Institution of Structural Engineers*. pp 246-259 (part 1, July) and pp278-288 (part 2, August)

