

Improving site specific modified driving formulae using high frequency displacement monitoring

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ABSTRACT

Results from high strain dynamic pile testing (PDA) of impact driven piles are frequently correlated to pile driving sets and temporary compression, to obtain site specific modifications of driving formulae. An accurate record of driving set and temporary compression is required to obtain meaningful correlations. Traditionally, pile sets and temporary compression are measured manually on the pile during pile driving. The development of high frequency displacement monitoring has enabled more accurate measurement of set and temporary compression. Data obtained using high frequency displacement monitoring of closed ended piles has revealed differences between the apparent set at around 200 milliseconds and the final set at around 1 second. Incorporation of this data into the signal matching process and the subsequent correlations with driving formulae resulted in a more consistent match. Recommendations are made to improve correlations with pile driving formulae.

1 BACKGROUND

Deep foundations are constructed to transfer loads from a superstructure into the subsoil. In order to minimise the risk of failure of the foundation elements, design methods take into account the uncertainty of the load and the resistance. Pile testing can reduce the uncertainty of the pile-soil resistance behaviour.

AS2159-2009 and Verification Method B1/VM4 both assign a lower value for the geotechnical strength reduction factor (ϕ_g) if the risk rating of a project is higher, and allow for an increase of ϕ_g if pile testing (such as static load testing or high strain dynamic testing) is conducted.

However, pile testing is limited by time and budget constraints, and it is highly unlikely that all piles on a project will be verified using pile testing methods. Static load testing can only reasonably be done on one or at most a few piles (Rausche et al., 2008) and high strain dynamic testing is generally limited to 5-15% of the number of piles (Seidel, 2015a). Therefore, alternative methods are required to ensure that the geotechnical behaviour of the remaining piles is within acceptable tolerances.

This may be done by simply comparing installation records of non-tested piles to installation records of tested piles and ensuring that non-tested piles have been driven to similar or harder conditions. In general practice, dynamic formulae, such as the Hiley formula (Hiley, 1930) are often used. For example, the Auckland Structural Group Piling Specification (2002) recommends its use, and it is accepted by AS2159-2009 as an appropriate method for pile load verification, providing the appropriate ϕ_g is used. The use of generic dynamic formulae has been the subject

of academic debate from as early as 1941 (American Society of Civil Engineers, 1941) and has continued to date (Allin, 2015). Allin recommends to use wave equation analyses instead of generic dynamic formulae for the assessment of untested piles. In wave equation analyses, predictions of driving behaviour are made using more detailed information on pile, hammer and soil interaction, thus providing more site specific relations between driving and geotechnical strength, when based on site-specific input. However, these more detailed analyses still use the set (permanent displacement per hammer blow) and an assumed driving energy to obtain R_{ug} from the wave equation predictions.

Auckland Structural Group (2002) states that the Hiley formula has its accuracy improved when adjusted for site-specific data. Seidel (2015a) proposes the use of site specific dynamic formulae, which are to be calibrated based on test data. This same approach would also be applicable to calibrating the results of wave equation analyses. In both cases, a relatively simple criterion for on-site verification of the geotechnical strength of untested piles can be provided, whilst incorporating test results. This paper will focus on the calibration of dynamic formulae, as these are most commonly used in New Zealand practice.

Both Allin (2015) and Seidel (2015b) emphasize the high variability in energy transfer from impact hammers and caution for the sensitivity of driving formulae and wave equation analyses to this parameter. Energy correlations that use a co-efficient of restitution to incorporate the energy loss associated with the impact between the hammer and pile should be used with caution. Given the sensitivity of driving formulae to this parameter, either measurements of energy in the pile should be used, or an energy efficiency factor should be applied based on measured data.

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.

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. A match quality number is computed based on the mismatch of computed and measured signals, as an objective measure of the match quality, independent of a visual or personal assessment (PDI, 2014). A lower match quality number indicates a better match. There is no unique solution to signal matching, and non-credible soil-pile models may result in a good match quality.

The dynamic testing equipment measures the maximum displacement of the pile using accelerometers, but does not distinguish between temporary compression and set. It is recommended that the set determined from actual measurements is used as input in the signal matching process, to improve the match quality (PDI, 2014). However, it should be noted that the

estimated geotechnical ultimate strength from signal matching is not very sensitive to the set input (PDI, 2014).

3 SITE SPECIFIC DYNAMIC FORMULA

The geotechnical strength resulting from the signal matching process can be used as input for the calibration of dynamic formulae for untested piles. Each pile test will provide at least one correlation between set and geotechnical strength. It is important to realise that this is relative to the energy imparted by the hammer.

Temporary compression of the pile is used as a proxy of hammer energy and dynamic soil response in the Hiley formula. Alternatively, the measured peak velocity of the pile can provide an indication of energy imparted. A third method to provide an indication of imparted energy is observing the maximum displacement (set plus temporary compression), as piles founding in similar stratigraphy at similar penetrations should have similar maximum displacement values, even if the sets are different.

The most basic approach to obtain a site specific dynamic formula is to eliminate the dynamic component from the formula. One method, developed by Seidel, applies a Dynamic Reduction Factor (DRF) to correlate the geotechnical strength derived from dynamic formulae ($R_{ug,DF}$) to the geotechnical strength obtained from signal matching ($R_{ug,SM}$) for tested piles. This relationship is shown in its simplest form in Equations 1 and 2.

The DRF is derived for all test piles, as follows:

$$DRF = \frac{R_{ug,DF,test\ pile}}{R_{ug,SM,test\ pile}} \quad (1)$$

It is subsequently applied to non-tested piles:

$$R_{ug,non\ tested\ pile} = \frac{R_{ug,DF,non\ tested\ pile}}{DRF} \quad (2)$$

Dynamic formulae typically predict driving resistance, which is a combination of static and dynamic resistance. The DRF approach aims to eliminate the dynamic resistance component, based on site specific tests. Since dynamic effects are a function of pile velocity, the DRF is not a unique value, but will be dependent on set if applied to piles driven in similar conditions (same size, maximum displacement, penetration and energy applied). In order to determine the relationship between DRF and set multiple tests are required at various sets, with the same input energy.

It should be noted that modified driving formulae are only to be used for piles driven to similar conditions and driving behaviour. This may require the development of multiple driving formulae for one project.

4 HIGH FREQUENCY DISPLACEMENT MONITORING

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 in the case described in this paper. The PDM has a sampling rate of 4,000Hz, and can be used at an offset distance of 6 to 20m from the pile (Advanced Foundation Technologies, 2015).

High frequency displacement monitoring can replace the traditional manual set card and provides a significantly higher level of detail (see Figure 1), as this eliminates the associated errors caused by human influence.

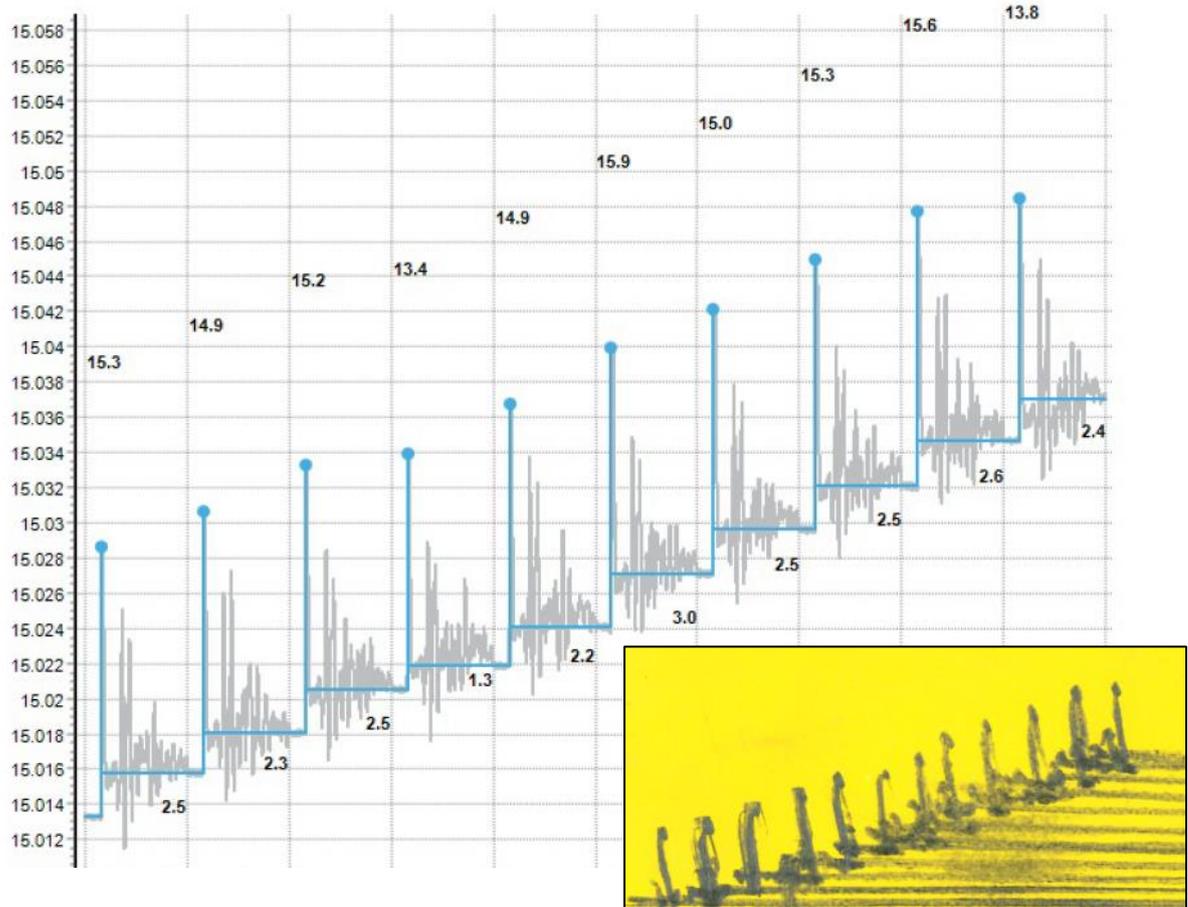


Figure 1: Manual set card results vs PDM results

The high frequency of the measurements provides more insight in the pile movement during driving, as is illustrated in Figure 2. In the record shown, a secondary movement is visible, which is caused by hammer rebound. Also, the lifting of the hammer can be distinguished, leading to a small upwards movement of the pile, as the mass is lifted off the pile.

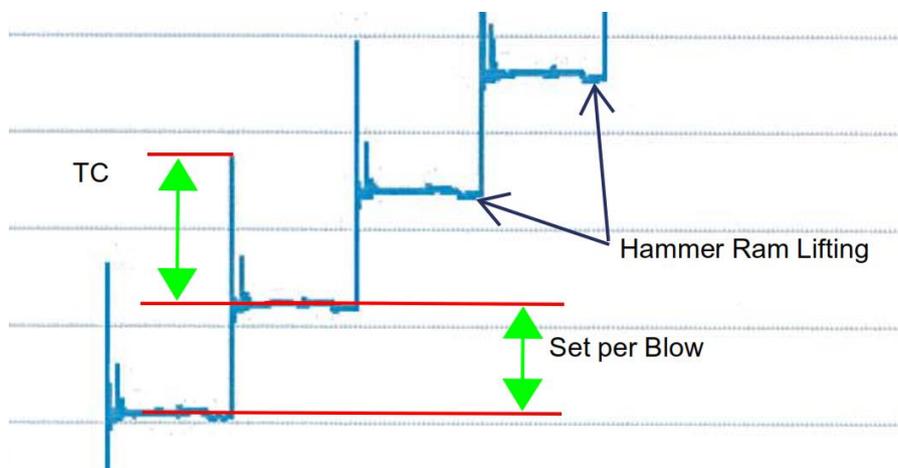


Figure 2: PDM record showing detailed pile movement

5 OBSERVATIONS OF SET RECORDING

The authors have conducted tests using high strain dynamic testing in conjunction with high frequency displacement monitoring. In several of these tests, the use of high frequency displacement monitoring has revealed a difference between the “short term set” at several hundreds of milliseconds after impact and the “long term set” at higher time increments. Figure 3 illustrates this with the short term set (3.8mm) occurring between $t = 0\text{ms}$ and $t = 400\text{ms}$ and the long term set (1.2mm) occurring at $t > 400\text{ms}$.

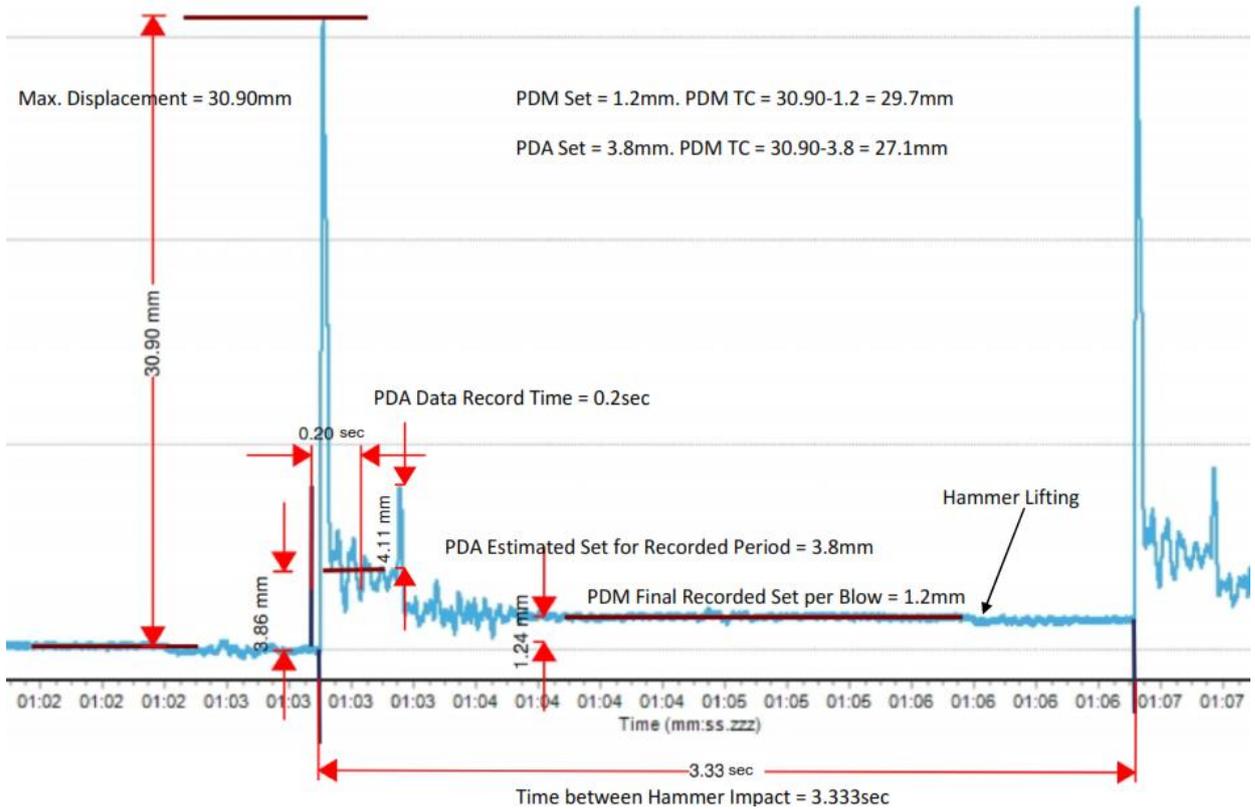


Figure 3: Short term vs long term set as recorded by PDM (Pile C27-EOD)

As discussed above, the match quality of the signal matching process used in dynamic testing is improved by the input of a measured set. Since the dynamic testing equipment records data for a relative short duration (up to 200ms as a default), the appropriate input for this would be the short term set. The set that would normally be recorded in a manual set card would be the long term set, as manual measurements are not sensitive enough to record the set at 200ms. Dynamic formulae would also incorporate the long term set.

Table 1 shows the sensitivity of both the signal matching and the (generic) Hiley formula for short and long term sets, based on the data shown in Figure 3, as well as a derived DRF.

Table 1: Sensitivity to short term and long term set (pile C27-EOD)

| Set type | t (ms) | Set (mm/blow) | Temporary Compression (mm) | Signal Matching R_{ug} (kN) | Signal Match Quality | Hiley R_{ug} (kN) | DRF (-) |
|------------|--------|---------------|----------------------------|-------------------------------|----------------------|---------------------|---------|
| Short Term | 200 | 3.8 | 27.1 | 5000 | 2.91 | 8,602 | 1.72 |
| Long Term | >400 | 1.2 | 29.7 | 5000 | 3.07 | 7,885 | 1.57 |

It can be seen from Table 1 that the signal matching process is not sensitive to the set. The match quality is slightly improved by using the correct short term set instead of the long term set. The geotechnical strength determined from the Hiley formula is however very sensitive to the set input.

Problems may arise when the displacement data from the high strain dynamic test shows a mismatch with the manually recorded set on site. If a better match is found with the short term set, it is the experience of the authors that practitioners assume the manually measured set to be incorrect and the mismatch due to inaccuracies in the method. As the presented data from high strain displacement monitoring shows, differences in observed set may be due to the time duration of measurements. This understanding is important to ensure that signal matching and field measurements are correctly correlated. Using high strain displacement monitoring can aid in the elimination of manual inaccuracies and a better understanding of actual displacement over time.

6 CONCLUSION

The use of high frequency displacement monitoring provides detailed information on the movement of a pile, thus providing more insight into the development of set and temporary displacements than manual set cards. It also provides a much higher accuracy and operator independency when measuring set and temporary compression, both of which are key input parameters of the commonly used Hiley formula. Additionally, measured pile velocities can serve as a proxy for energy input, when correlated with high strain dynamic testing.

The use of high frequency displacement monitoring revealed differences between the short term set and long term set. Signal matching of one dynamic test pile was conducted using both the short term and long term set. Incorporating the short term set in the signal matching process did not lead to changes in the estimated ultimate geotechnical strength. The signal match quality was slightly improved. The long term set should always be used as input of formulae. The short term set should only be used for the signal matching process.

From the initial analysis, the geotechnical strength estimates of the signal matching do not seem sensitive to the set input. The authors intend to conduct further analyses on a greater data set to confirm this finding.

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