Improved interpretation of high strain dynamic test results using high frequency displacement monitoring of closed ended piles

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ABSTRACT

Signal matching of high strain dynamic testing (PDA) results requires the input of a pile driving set. Traditionally, this is measured manually, which leads to considerable systematic errors in the measurement of set. The development of high frequency displacement monitoring equipment allows for much more accurate measurement of set and temporary compression. This paper discusses pile testing data of closed ended piles, using high frequency displacement monitoring in conjunction with PDA testing. It was found that the (apparent) set measured at approximately 200 milliseconds differs from the final set measured at 1 second after impact. Incorporation of this data into the signal matching process and the subsequent correlations with driving formulae resulted in a more consistent match. The possible causes for the difference in set, as well as implications for pile verification are discussed.

Keywords: pile testing, displacement monitoring, PDA, pile set, residual stress

1 INTRODUCTION

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

High strain dynamic testing infers dynamic resistance to driving, using strain transducers and accelerometers attached to the pile. A back analysis process called signal matching is required to eliminate dynamic resistance components and obtain an estimate of the (static) nominal geotechnical resistance R_n (Hannigan et al., 2016). Signal matching is performed on integrated measurements of strain and acceleration. The actual permanent pile displacement per hammer impact (commonly called "pile set" or "set") can be used to correct integration errors of the velocity signal. It is usually determined from manual measurements on the physical pile.

High frequency displacement monitoring uses optical technology to measure vertical pile position (and therefore displacement) at a high sampling frequency. The use of high frequency displacement monitoring has revealed differences between pile sets at approximately 200 ms and those occurring at longer time intervals (i.e. more than 1 second). This was first reported by the authors for a single case study (Damen and Denes, 2017), which also discussed the possible implications for modified dynamic formulae in detail.

The authors have encountered many cases in which the pile set as evaluated based on the velocity signal only differed significantly from the set physically measured on site. This current paper discusses a larger data set and further investigates the impact on the signal matching process.

2 HIGH STRAIN DYNAMIC TESTING

High strain dynamic testing is a pile testing procedure that uses strain transducers 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 mobilized 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, a compression wave or a combination thereof are 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 resistance (dynamic and static) of the pile. Additionally, the measurements provide information on the total amount of energy transferred into the pile, integrity as well as the compressive and tensile stresses.

The inferred resistance obtained from the measurements includes the dynamic resistance of the pile-soil interface. In order to infer the nominal geotechnical resistance (R_n) 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 et al., 1991). Further accuracy is obtained by conducting an iterative back analysis process called signal matching, in which the measured signal is compared to a signal that is generated by a wave equation model. An experienced engineer adapts the model until the match between calculated and measured signal can no longer be significantly improved. A measure of match quality 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 (Pile Dynamics, 2014). A lower match quality number indicates a better match between the calculated and measured signal. It must be noted that signal matching is dependent on the user, and that the process does not yield a unique solution. In this paper, the authors followed the same signal matching method for consistency.

Accelerometers used in high strain dynamic testing can evaluate the maximum total displacement of the pile during impact. This total displacement consists of the temporary pile compression and permanent pile displacement per impact (pile set). In order to improve the match quality, it is recommended that an accurately measured pile set is used in the signal matching process, to correct integration errors on the acceleration data. It is noted, however, that estimated geotechnical ultimate strength from signal matching should not be very sensitive to the set input (Pile Dynamics, 2014).

3 HIGH FREQUENCY DISPLACEMENT MONITORING

Traditionally, pile displacement is measured on site by manual methods ("set card", see Fig. 1). Total maximum pile head displacement consists of a permanent compression (pile "set") and a temporary compression ("rebound").

In order to measure temporary compression, which is an important input in many dynamic driving formulae, an operative must be in close vicinity to and even in physical contact with the pile to measure pile movement.

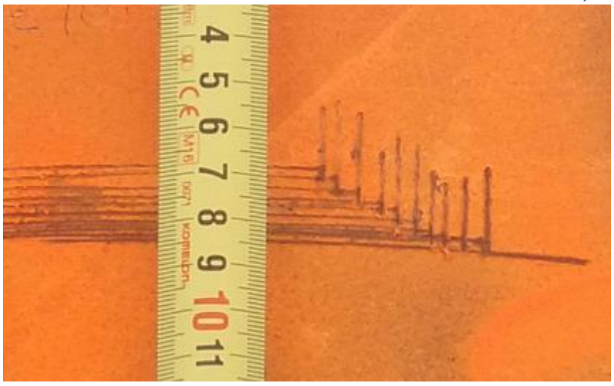

Fig. 1. Manual set card

High frequency displacement monitoring was developed to both reduce the safety risk of this technique and to enhance the quality of set and temporary compression measurements. The high frequency displacement monitoring device used to obtain the data in this paper is the Pile Driving Monitor (PDM), which uses optical sensors and high power light emitting diodes (LED) in combination with reflectors on the pile and measures pile position (of a selected location at the pile, usually near the pile head) at a high frequency (4,000 Hz) (Foundation QA, 2019). The absolute resolution of the system is +/- 0.1 mm.

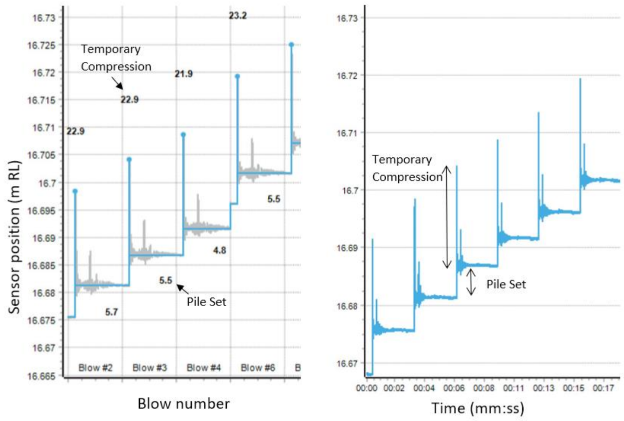

Fig. 2. Schematized record from high frequency displacement monitoring (using PDM) (left), as well as actual pile position measurement (right).

Fig. 2 shows example output of the PDM, with set and temporary compression inferred by the software for selected blows (left), as well as the actual measurement of vertical pile position at the location of the reflector (right). Fig. 3 shows the device in operation.

Fig. 3. Example of pile driving monitor set up on site, with reflector sticker on pile.

High frequency displacement monitoring can replace the traditional manual set card, as both temporary compression and permanent set can be inferred from the high frequency pile position measurements. Manual set cards are highly operator dependent and carry significant risk of inaccuracy, in addition to the health and safety risk. High frequency displacement monitoring is operator independent and provides a significantly higher level of detail (compare Fig. 1 and 2).

4 CASE STUDY

This case study discusses piles that were driven as part of a berth upgrade, in Queensland, Australia. The piles consist of closed ended circular hollow steel sections with an internal diameter ranging from 457 to 813 mm and a wall thickness of 14.3 to 18.3 mm. All piles were impact driven using a Junttan HHK-9S hydraulic impact hammer. A total of 8 piles were tested using high strain dynamic testing at end of drive using a Pile Driving Analyzer (PDA). The Pile Driving Monitor (PDM) was used as the method of high frequency displacement monitoring to measure set and temporary compression during the test, instead of manual set cards.

Fig. 4 shows a record from the high frequency displacement monitoring. It can be seen from Fig. 4 that the short term set measured up to approximately 200 ms after the blow (5.3 mm) differs from the set at longer time intervals (2.9 mm).

Fig. 5 summarizes the “short term set” obtained at 200 ms versus the “long term set” measured at 1000 ms for all test piles in this case. The long term set generally remains stable after 1000 ms. A small decrease (i.e. pile moving upward) is seen just before impact, which is indicative of the hammer weight being lifted from the pile.

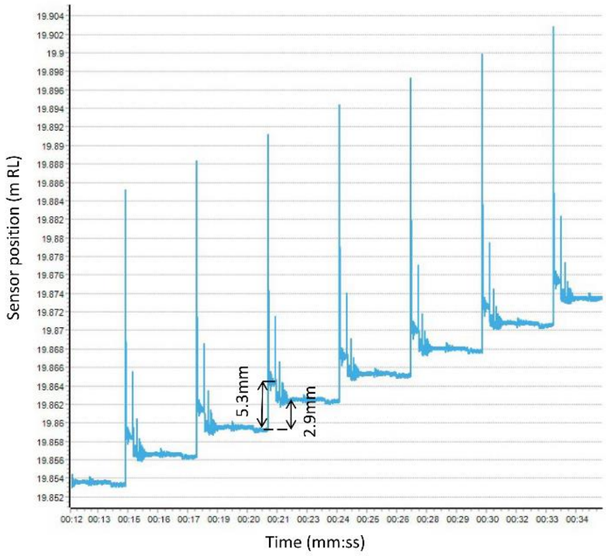

Fig. 4. High frequency displacement monitoring record for Ø610 mm case study pile, showing the difference in short term and long term set.

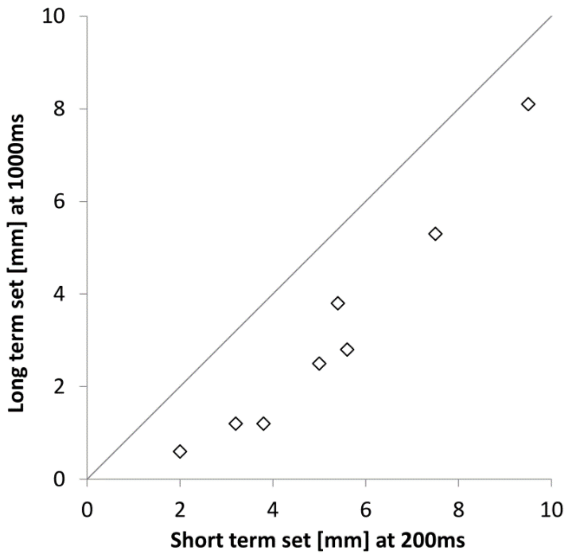

Fig. 5. Short term versus long term set as measured by high frequency displacement monitoring.

The short term set, measured at 200 ms, can be considered an “apparent” set, which is only present for a short duration (but not as short as the elastic temporary compression which has a typical duration of approximately 10-30 ms). This set would not be registered accurately if a traditional manual set card is taken, and is only revealed when pile displacements are monitored at high frequencies. However, the typical timeframe that is used in high strain dynamic testing is generally from start of hammer impact to 200 ms thereafter (timeframes may differ depending on wave speed and pile length, but 200 ms is commonly used and is illustrative for the effects observed in this case study). Since pile set is an input in the signal matching process, as discussed above, the apparent short term set at 200 ms would be the appropriate input parameter.

In order to assess the sensitivity of the signal matching process to the short term set, the authors have conducted signal matching using the program CAPWAP, for both the long term and short term sets for each pile test. The pile-soil model used in the back analysis was changed until no improvement in match quality could be obtained. The resulting estimated geotechnical nominal strength (R_n) for both cases has been compared and is summarized in Fig. 6. The match quality obtained for both cases is shown in Fig. 7.

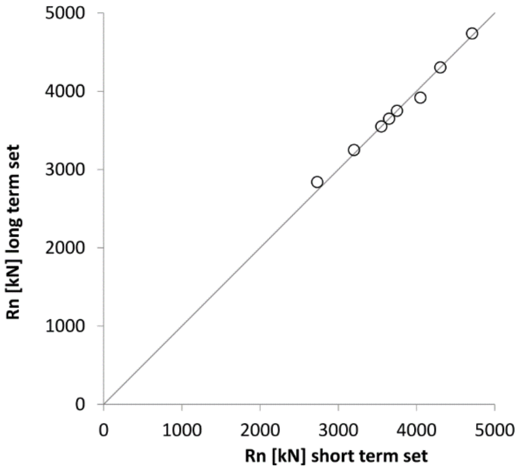

Fig. 6. Nominal geotechnical resistance (R_n) as obtained from signal matching using short term versus long term set.

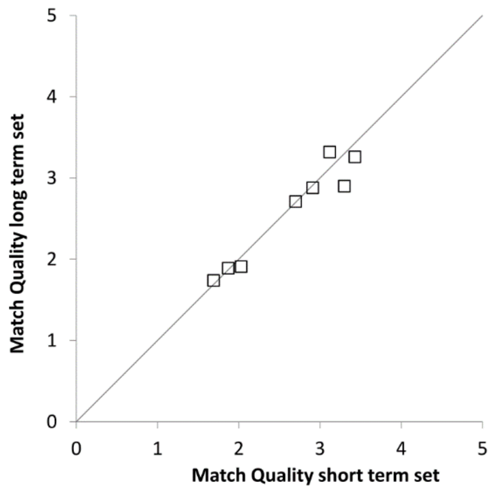

Fig. 7. Match Quality Number as obtained from signal matching using short term versus long term set.

As can be seen from Fig. 6 and 7 no significant change to R_n was found, nor was the match quality affected significantly. These findings support the statement that the result of the signal matching process is not very sensitive to set input (Pile Dynamics, 2014).

Although the signal matching process appears not sensitive to set input, it is still important to recognize the possible differences in short and long term set. When data is captured using high strain dynamic testing, and further analyzed with signal matching, the engineer may infer a set from the acceleration data of the PDA at shorter time intervals (e.g. 200 ms) that differs from the long term set measured manually on site. It is the experience of the authors that in many cases the inferred (short term) set is used in the back analysis, rather than the measured set, which can be understood, given the inaccurate and operator sensitive nature of the manual set card method.

Whilst this is not likely to significantly affect the inferred nominal resistance against static loading, care should be taken when this inferred set is subsequently used in verification methods for untested piles, such as wave equation analysis or dynamic formulae. If the inferred set is used as the basis of these verification methods, incorrect site-specific correlations between nominal resistance and set may be obtained. If engineers were to be conscious of the possibility that short and long term sets differ, the correlation process may be improved.

Generally, the short term set should be used for signal matching and the long term set should be used for obtaining site-specific verification correlations, such as improved dynamic formulae. Additionally, the use of high frequency displacement monitoring, in lieu of manual set cards, will enhance the accuracy of set and temporary compression measurements.

5 FURTHER REVIEW

In order to further explore the sudden change in set, the authors have examined the displacement data from the integrated PDA acceleration measurements at a time interval longer than 200 ms (see Fig. 8).

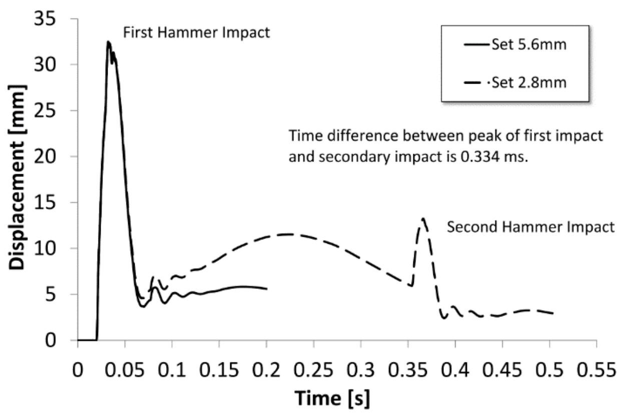

Fig. 8. High strain dynamic test data (displacement) from start of impact to 200 ms and 512 ms, indicating secondary hammer impact, adjusted to short term and long term set, respectively.

It should be noted that the displacement curves are adjusted so that the final point matches the set input obtained from the high frequency monitoring (5.6 mm at 200 ms and 2.9 mm at 500 ms). From this data it can be seen that there is a second, lower energy, hammer impact, which is likely caused by the hammer rebound. The time of this secondary impact coincides with the reduction in set, i.e. the pile moves back up, rather than further down.

A possible explanation is that the hammer energy of the initial impact was sufficient to overcome the shaft and toe resistance, and thus mobilizing the pile downward, but was insufficient to unlock the residual stress during pile unloading. The second impact, although too small to mobilize the pile downward, can have unlocked the residual stresses, thus allowing full unloading of the pile.

10 CONCLUSIONS

The use of high frequency displacement monitoring on impact driven closed ended circular hollow steel sections revealed a difference between observed set at 200 ms and 1000 ms.

The short term set would be the appropriate input for signal matching of high strain dynamic test data, which generally captures data up to 200 ms after start of hammer impact. No significant change in inferred nominal geotechnical resistance and match quality was found by applying the short term set instead of the long term set in signal matching. However, it is important to use long term measured set for the determination of site specific verification correlations for the use on non-tested piles, as this aligns with the actual measurements on site. If engineers understand that the dynamic test data can indicate a higher short term set, incorrect assumptions in the correlation process can be avoided.

Further investigation of the mechanism is recommended. Future research should include larger data sets, different pile types and different ground conditions. Discussion of the mechanism in future manuals on high strain dynamic testing and signal matching may be beneficial.

It is acknowledged that surface waves from e.g. piling may affect high frequency displacement monitoring. However, the authors do not consider the effects of surface waves to have significantly impacted the observations discussed in this paper.

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