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Observing Friction Fatigue on Calcareous Material

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ABSTRACT: This case study describes the results of dynamic testing and CAPWAP® analysis on open ended steel tubular piles driven into calcareous material. PDA monitoring of the complete driving process has enabled observation of a progressive breakdown in shaft friction, otherwise known as friction fatigue. A series of CAPWAP® analyses, undertaken at varying penetrations, demonstrate the progressive loss of pile shaft resistance during driving to a residual strength value. Previous research has demonstrated that friction fatigue is associated with pile length, and more recent investigations show that it is more likely associated with cyclic motion. The mechanism involved is discussed that provides an explanation for this loss of shaft resistance which is thought to be attributed to the progressive degradation of localised materials at the pile/soil interface due to the continuous shearing that is generated as the pile is driven. Using CAPWAP® to evaluate the progressive changes in the distribution of shaft resistance provides important insight into the phenomenon of this break down in shaft resistance at a macro level. Nevertheless, it appears that shaft resistance degrades to a residual value.

1 INTRODUCTION

The behaviour where a soil loses resistance around the shaft during driving or cyclic loading is termed friction fatigue. This phenomenon was first observed with piles installed in calcareous sands as described in literature since 1973 (Angemeer et al) and has since then been the subject of academic study (e.g. Murff 1985, Poulos 1989, White and Bolton 2002). By using dynamic testing methods to measure the complete installation of a pile, the variation of shaft resistance distribution as a function of pile penetration can be inferred.

This case study focuses on a project off the north-west coast of Australia. The first dynamic test pile occurred at a penetration of 23.5m and several days later at a penetration of 43.5m. At both penetrations, the driving set was 4mm per blow using the same hammer and drop height. It is this difference in penetration and the similar set per blow that raised issues with the shaft frictional resistance. Therefore a particular pile (F1) was chosen for detailed assessment to be monitored over an installation length of 39 meters. The aim of the study is to observe friction fatigue using PDA and undertake CAPWAP® modelling to determine if there is a reduction/fatigue of shaft resistance around the pile.

The pile tested is a 508mm outside diameter open ended steel tube with a 12.7mm wall thickness with no toe thickening or plate. A 1.3t hydraulic drop hammer with a maximum drop height of 1.3m was used for installation for the entire pile penetration (LP) length of 39 meters.

2 BACKGROUND

2.1 *PDA-CAPWAP®*

Dynamic pile testing, also known as Pile Driving Analyzer (PDA) testing, is a technology which was developed in 1960 (Smith) and commercially available in the 1970's by Pile Dynamics, Inc. (PDI). Strain and accelerometers gauges are attached to a pile and capture strain/acceleration time records for each hammer/pile impact. The information recorded is both the stress-wave from the hammer and the reflected stress-waves generated along the pile length as well as from the pile toe. These stress-waves can be interpreted using wave analysis programs such as CAPWAP®, in order to determine the total capacity and the distribution of the capacity along the shaft length and at the pile toe. The program CAPWAP®, developed by Goble and Rausche (1979), is generally accepted to be the definitive method on interpreting dynamic pile records. It is based on modelling the pile as an elastic body, with both mass and stiffness, and the surrounding soil as a series of elasto-plastic static resistance springs and linear dashpots. Actual soils do not follow simple elasto-plastic behaviour and are more typically non-linear, but CAPWAP® in most cases has shown proven reliability providing that a sensible and realistic model has been applied. To make a rational and valid CAPWAP® model, the engineer should have all information at hand, including hammer details, driving records, set measurements, geotechnical conditions and pile details. The theory of PDA and CAPWAP® will not be further discussed within this paper.

2.2 *Pile Design*

Prior to the realisation that calcareous sands behave differently to terrigenous sands, determination of shaft resistance was based on standard or 'conventional' methods which are still currently used today. These methods were initially applied to all types of sands, both silica and calcareous. It was not until the 1970's (Angemeer 1973) and the 1980's (i.e. North Rankine A – Senders et al. 2013) that pile test results observed shaft resistance values well below the 'conventional' design.

The standard conventional methods involve the use of overburden stress and a frictional co-efficient between the pile type, soil and the earth pressure co-efficient, K. (Johannessen and Bjerrum 1965, Chandler 1968 adopted slightly different approach). Other methods involve correlations between collected in-situ testing (such as SPT). A number of foundation textbook even advise to limit the maximum skin friction, which is proven incorrect (Kulhawy 1984). More modern methods for shaft resistance are based on CPT (Kelly and Wong 2005) and on the expansion cavity expansion theory where there is an increase in radial stress related to dilation effects. Using the cavity expansion approach removes the 'K' value and the overburden stress, both being replaced with the effective radial stress acting on the shaft at failure and the critical state sand interface angle of friction, which is developed when the soil at the interface has ceased dilating or contracting (i.e. zero volume change).

2.3 *Friction Fatigue*

Friction fatigue is the destruction of the surrounding material due to excessive shear stresses, thought to be related to the following:

the 'h/D' effect (Randolph et al 1994). (Figure 1). This is associated with the decrease of horizontal effective stress (radial/normal stress) as the pile penetrates deeper. Hence the higher the h/D ratio below a nominated depth, the larger the decrease in shaft resistance;

a repetition of shearing the soil at the pile/soil interface produced by movement of the pile (this is referred to as a cycle – i.e. a pile hammer blow);

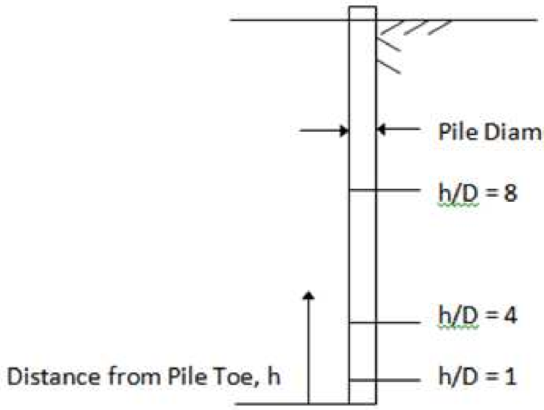

Figure 1. h/D Effect

Figure 2. Hollow Structure – Coralline Rock

3 CALCAREOUS SANDS

3.1 *What is it?*

Calcareous material is a generic description given to granular soil composed of calcium carbonate. It is formed from shells and skeletal remains from benthos organisms (bottom dwelling) such as coral, molluscs and calcareous algae. Closer inspections of these biogenous sediments reveal a porous hollow structure, with a rough surface (Figure 2).

3.2 *Engineering Properties*

Calcareous sands are special because they do not behave like normal sands. They have a higher void ratio due to the hollow structure and therefore tend to crush more readily compared to lithogenous sediments (quartz sand). These sands may be found in cemented or uncemented states. At first there is some strength to the grain due to the material and potential cementation effects. But once a certain pressure is exceeded, it crushes quickly. Trying to determine the initial nature of calcareous materials is quite difficult. For example, undertaking SPT testing involves damaging the possible cementation bonds.

The friction angle is generally quite high, typically above 35 degrees and often exceeding 50 degrees (Murff 1987). It is noted that even partial cementation can cause 'arching' around the pile, hence the sand can effectively self-support itself, not applying a great deal of lateral pressure to a pile. Poulos (1989) showed that under a series on monotonic loading on calcarenite core samples, that the normal stress reduces as shear displacement increases. These tests are quite important as they demonstrate the volume change characteristics for calcareous material where initial contraction leads to a continued reduction in the post peak strength at the interface.

3.3 *Friction Fatigue and Calcareous Material*

White and Bolton (2002) discuss that friction fatigue is related to pile movement. Experiments observed the decrease in horizontal stress at a nominated depth below ground level as the pile toe passes this nominated point and continues further beyond. They observed that a zone of sand beside the pile underwent volume reduction reducing the normal stress. White and Lehane (2004) undertook laboratory experiments using instrumented piles to determine if friction fatigue is related to the h/D ratio. The piles were installed in one of three ways: 1. Monotonic; 2. Jacked – cycles of fixed downward displacement and 3. Pseudo-dynamic – comprising of a downward then upward displacement. Results from the Monotonic loading showed only a minor decrease in shaft resistance with increasing depth. However, the jacked and pseudo-dynamic showed significant degradation of shaft friction with the results showing that it is related to the number of cycles that had occurred beyond the soil horizon, not the h/D ratio. This observation is quite unique because it eliminates the h/D effect alone based on the monotonically installed piles. However, for piles that are installed under cyclic condition, it is shown that it is the number of cycles that influences the reduction in shaft reduction.

3.4 *Shear Resistance Values for Calcareous Material*

Observations (Angemeer et al 1973) from a series of load tests on driven piles showed the capacities were approximately 20% of those predicted by conventional methods. Murff (1985) listed a number of test results from 1973 to 1985 and observed mean peak values ranging between 13.4 to 20.3 kPa. Aggarwal et al (1997) further defined skin friction resistance relating to percentage of calcium carbonate, where above 45% shaft resistance is approximately 28kPa. Poulos (1989) provided peak skin friction values ranging between 10 to 20kPa for uncemented material. Residual friction values ranged between 5-20kPa for various cementation levels. Ghazali et al (1990) discussed limiting skin friction to 20kPa.

4 FULL MONITORING OF PILE F1

The final penetration for Pile F1 was 39m below sea bed level. PDA monitoring commenced from 6m. Data collected was of good quality and four strain gauges were used for the last 33m of driving due to slight hammer alignment issues. There was a total of 7226 hammer hits (or cycles) from the start of driving. The set vs penetration is shown in Figure 3. As the hammer drop height is consistent, the set per blow variation gives an indication of the strength of the material at the toe of the pile. Hence a smaller set may indicate stronger material, or higher cementation.

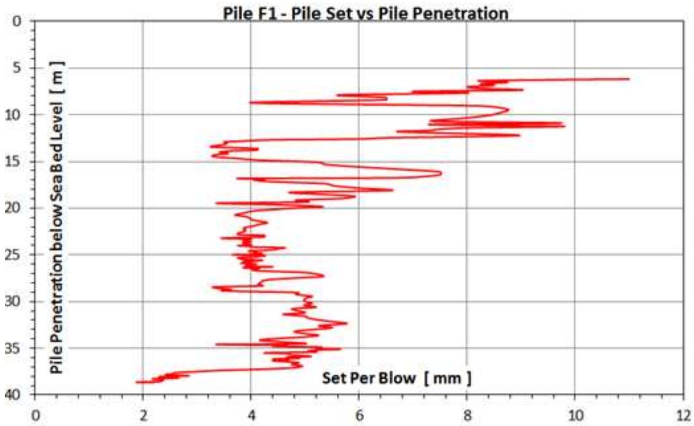

Figure 3. Set vs Penetration

4.1 *Site Geotechnical Model*

Due to the remote location of the work site, a geotechnical investigation was not undertaken at the work site location. Therefore the geological environment is based on a desktop study, local observations and geotechnical reports in similar environments. The geological age is Late Quaternary to Recent. It is composed of bedded marine calcarenite, thick reefs, calcareous sand and talus (limestone) deposits. The generalised profile for the test site is as follows: Upper 15m comprising of calcareous sandy sediments, carbonate sands, coral, phosphate sediments, and talus. Areas may be cemented. Below 15m – porous limestone layers, varying degrees of cemented sand layers, sand layers composed of coral, coralline limestone, shells, carbonate sands and silts.

4.2 *PDA Observations of Pile F1*

PDA testing captures the downward generated compressive stress wave (from the hammer impact) and the subsequent reflections. The data is generally presented by viewing force/velocity time records, or more commonly used view of Wave-Up (WU) and Wave-Down (WD). The WU trace gives a visual guide of the dynamic soil resistance around the shaft of the pile. As the wave travels down (WD) the pile, the pile moves downwards and displaces the soil around which 'slips' past the pile around the perimeter. This slipping is referred to as mobilisation, which is displacement vs shear resistance. This soil resistance is partially reflected as compression waves where these reflected waves are cumulative added together to generate the WU response. To further demonstrate this, Figure 4 shows the WU response and an indication of the shaft resistance on the pile. As the WU line increases, the shaft resistance on the pile increases. Therefore if the pile is PDA monitored for the full penetration, then by comparing the WU response, we are able to visually assess how the shaft resistance around the pile behaves.

The Wave-Up response for various penetrations of pile F1 is shown in Figure 5. The response has been modified to only show length of penetration (i.e. the pile toe response has been removed). The changes in the response are quite dramatic at certain locations. For example the response at LP 13.7 and 17m are much higher compared to the other response. This correlates with the sets being lower per blow indicating harder ground conditions. Once the pile penetrated beyond 17m, the response drops of significantly. This example demonstrates that the shaft resistance is reducing as the penetration is increasing due to driving. At the final penetration, it is noted that the WU response seems to come to a final 'residual' line following the same trend for 33m.

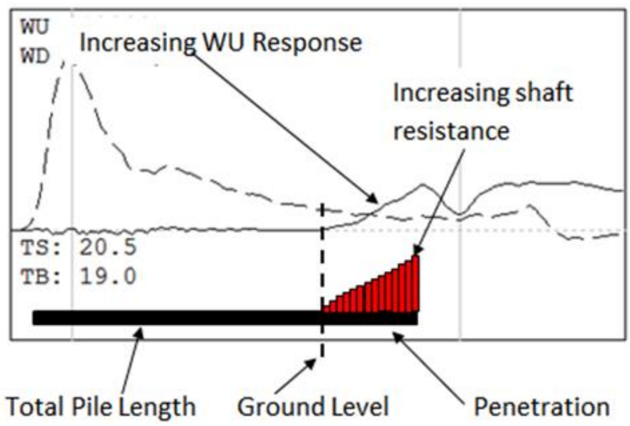

Figure 4. Interpretation of Wave-Up Response

The WU response eventually becomes a downward slope once the penetration reaches 25-30m and beyond. Generally, the WU increases with respect to increasing skin friction resistance which represents that the shaft resistance is increasing with depth. When the WU starts to 'flatten' or even reduce this may indicate that the shaft resistance is decreasing in strength or it is associated with pile unloading (an upward movement of the gauges as the pile bottom is still moving downwards), or a combination of both. When there is unloading in PDA data, a CAPWAP® analysis is required to model the effects of unloading on the WU response to determine if the decrease in the response is caused by lower shaft resistance values. Therefore, the straight forward visual approach of using WU to indicate the shaft resistance model is not applicable from when the unloading section begins. Therefore, if there is a weaker layer, CAPWAP® will model this.

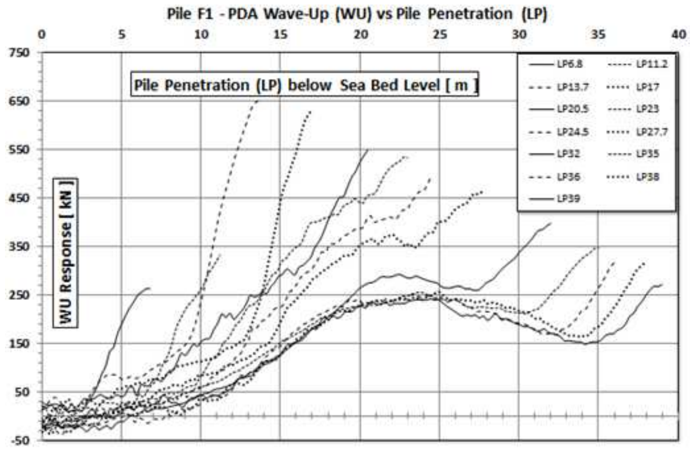

Figure 5. Wave-Up Response for Various Penetrations

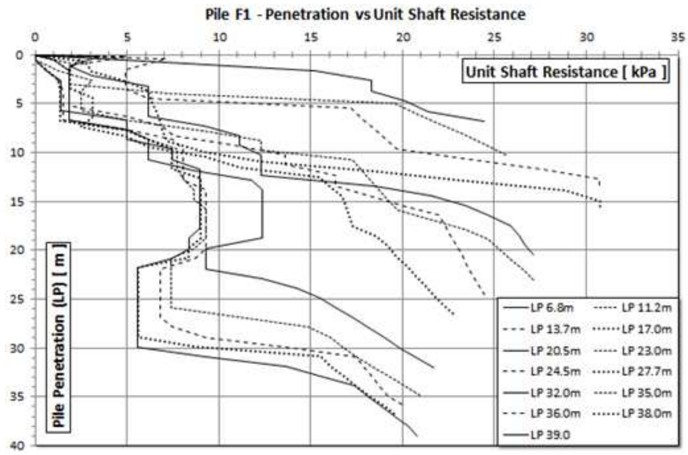

Figure 6. Shaft Resistance Values Vs Pile Penetration

4.3 *CAPWAP® Analysis and Observations for Pile F1*

A CAPWAP® Analysis was undertaken for each of the penetrations as shown in the PDA Wave Up response. The total unit shaft resistance at each meter of shaft vs penetration is shown in Figure 6. The results are representative of the PDA data, which show similar trends to the WU responses. Using the depth at 13m as an example, the modelled total unit shaft resistance based on the data from LP13.7m is 30.7kPa. At the same depth location but looking at the results from the CAPWAP® at LP38m, the total shaft resistance is 7.8kPa. This is a decrease of approximately 75%.

In all CAPWAP® analysis, it is the bottom 1-2meters of the pile that has the highest unit shaft resistance. This may be expected because the pile has just been driven into virgin material, where the surrounding soil is trying to be 'pushed' to the side of the pile. As the calcareous sand particles are trying to dilate, there is an increase in horizontal stress which increases the shear stress which initiates collapse of the sand. Associated with this collapse is volume reduction. This is also evident, as the unit shaft resistances 4m above the toe (or an approximate h/D ratio of 8) are up to 40% lower compared to the initial value.

From the CAPWAP analysis, the values below are given as total kPa values acting on the external section of the pile. Therefore, depending on what percentage is acting internally, the values may be less: Peak: 20.7-35kPa, Residual (LP3-7): 1.3kPa, (LP15-20) 9kPa, (LP22-30) 5.5kPa, Average 5kPa, which is similar to what has been observed in literature.

To determine if friction fatigue is related to penetration (the h/D ratio) or to the number of cycles, further investigation is required using the CAPWAP results. The following depth locations below sea bed level will be used for this analysis, which are: 5, 15 and 25m depths. For this, the total external shaft resistance values have been converted to percentage decrease from peak shaft values using the initial first peak shaft value determined at each depth.

Figure 7 compares the % shaft resistance decrease vs the number of blows encountered below each nominated depth location. This shows that at each of the 3 penetrations, there is a break down in shaft resistance ranging from 70 to 90% from its initial shaft resistance value over a period of 3000 to 4000 cycles. All three depths show an approximate linear decrease starting at 100% which flattens out to a potential 'residual' value. Figure 8 shows the % shaft resistance decrease vs the h/D ratio. This now shows that the decrease in unit shaft resistance ranges from 70-90% for an h/D ratio ranging from 21 to 33, an average ratio of 27. It is noted for both that a trend begins to appear where the unit shaft resistances show a similar degradation/fatigue pattern for both.

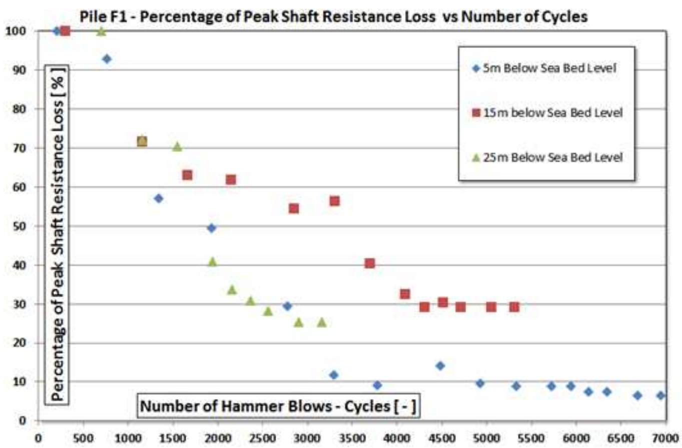

Figure 7. Percentage Shaft Loss vs No. of Cycles

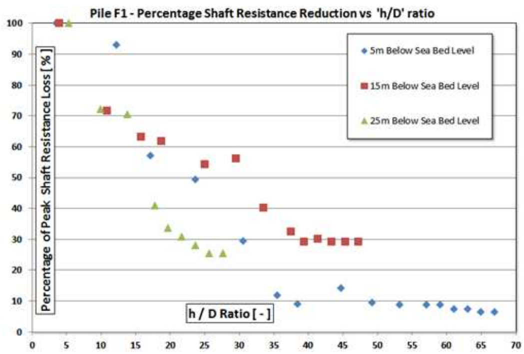

Figure 8. Percentage Shaft Loss vs h/D Ratio

Summarising the above information, the best visual trend is seen in Figure 7 (Percentage Peak shaft loss Vs Cycles) where all 3 penetrations seem to align to approximately 60% (a 40% decrease). After that, the 5 and 25m locations follow each other, while the 15m location takes a slightly different path. Figure 8 (Peak Shaft loss compared to h/D ratio) still shows a visual trend for all 3 locations, but is more scattered. It appears that friction fatigue is better associated with the number of cycles applied compared to h/D ratio based on visual assessment of trending data. It is also interesting to note that both methods observe a 'residual' value, which is a loss in shaft resistance from 70 to 90% of its original peak value.

The above review is quite unique to observe a pile with over 7200 cycles. These observations seem to correlate with the data observed from White and Lehane (2004). Unfortunately, laboratory models cannot reproduce this type of analysis due to scaling effects and model size limitations, with respect to pile displacements per blow.

5 CONCLUSION

This case study focused on the observation of friction fatigue in calcareous material using Pile Dynamic Testing (PDA) to observe the changing nature of the shaft resistance by recording the response wave for every cycle. The response wave is generated by in situ shaft resistance and the cycles are generated from a driving hammer. Results from Pile F1 showed that PDA is an interesting and suitable vehicle for observations of friction fatigue and provides an insight to what is occurring in real time. CAPWAP® modelling of the pile at various penetrations allowed the determination of peak and residual shaft resistance which correlated quite well to existing literature from the past 40 years. The shaft resistance values allowed further analysis by comparing the fatigue in the shaft resistance values to be compared to the number of cycles as well as the penetration, or h/D ratio, to observe if there is a relationship with either method. Overall, the number of cycles compared to shaft degradation seemed to best represent friction fatigue which was based on the observation of 3 different penetrations and comparing the unit shaft resistance which showed better trends compared to h/D. This case study has provided a direct and unique insight into the phenomenon of friction fatigue.

6 ACKNOWLEDGEMENTS / INFORMATION

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