Are we modelling the wrong pile? – Is it time to improve pile testing analysis?

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ABSTRACT

The majority of cast in-situ pile load testing for resistance verification is undertaken using high strain dynamic testing where a hammer strikes the top of a pile, imparting a one-dimensional stress wave down the pile. This 'stress wave' is captured using strain and accelerometer gauges to produce force and velocity readings, which are equal when the velocity is multiplied by the pile impedance. The impedance is a function of concrete modulus, concrete wave speed and cross-sectional area. Case Pile Wave Analysis Program (CAPWAP) is signal matching software where the captured force and velocity data are analysed to determine the static soil resistance with respect to the pile head deflection. CAPWAP is a numerical analysis program where the pile is divided into a series of segments, each with individually uniform properties (Impedance). For prefabricated piles, such as reinforced precast, or prestressed concrete, the impedance is uniform for the full length. However, for bored piles, the cross-sectional area can vary with depth, and hence the impedance can vary significantly, especially in soft soils. In many cases, the pile model used in a CAPWAP analysis is not adjusted to reflect the as-constructed pile geometry and only the pile impedance is modified or guessed. Effectively, this is trying to model the static resistance of a pile with a pile model that is not geometrically accurate. This approach to modelling without an accurate pile model can lead to an overestimation of static resistance. There is now technology readily available that can assist with determining the actual cross-sectional area over the full depth of the pile. This paper presents the comparisons of using design vs actual cross-sectional area profiles in soft soil environments. Modelling the actual area increase can lead to more accurate and representative shaft resistance determination.

Keywords: Pile testing, signal matching, bored piles, foundations

1 INTRODUCTION

High strain dynamic testing (HSDT or PDA) is a standard method for pile load verification adopted across Australia. This system was initially applied to uniform piles, such as preformed concrete and steel piles where the area is known to be consistent prior to pile installation.

The application of HSDT transitioned to cast in-situ piles, which are typically non-uniform with respect to cross-sectional area over the pile length. The cross-sectional area profile is a function of the construction method (open hole vs continuous flight auger), control measures (temporary or permanent casing / drilling fluids) and ground conditions (soft soils, hard rock, etc.).

In locations where soft soils are present, such as the Docklands in Melbourne, the area increase for cast in-situ piles may be very large, sometimes up to double the design diameter, depending on pile design and construction techniques. Therefore, it is desirable to know the pile profile for any cast in-situ pile when undertaking HSDT.

This is important when testing is used to determine the total geotechnical resistance of the pile, including the resistance available from the shaft. Furthermore, the Australian Piling Code AS2159-2009[1], notes: "This testing technique has been applied to other pile types, including timber piles (tapered) and cast in place piles. The successful interpretation and analysis of such piles has to be accompanied by reliable information on the pile geometry".

Overall, the more accurate a pile profile used to determine static resistance, the better the results.

Generally, when the HSDT data is used to undertake further assessment using signal matching software, such as CAPWAP[2], the typical approach is to assume the design pile diameter or make an assumption of a certain percentage of overbreak (additional concrete).

An unknown pile profile can significantly affect the determination of the pile resistance and other results, such as stresses, shear strength calculations and integrity assessment.

When using signal matching programs, the input requirement is force and velocity (multiplied by impedance). Impedance is a function of concrete modulus, wave speed and cross-sectional area. As the modulus is a function of the wave speed (with respect to density), if there is a change in the impedance, it is generally assumed that this is due to a change in the cross-sectional area.

As built construction records, such as actual placed volume, concrete curves, CFA records, construction technique and ground condition will assist with defining a more accurate pile geometry; however, a great deal of interpretation is required, and the modeller is essentially guessing a pile profile model based on the available information.

There are now techniques and technology that can assist with evaluating the pile geometry with depth. The objective of this paper is to present an example from the effects of altering the pile profile, and then present a case study showing the benefits of using the actual pile profile.

2 BACKGROUND

In the early 1980s, HSDT was used on the West Gate Freeway project in Melbourne, where testing with a 20t hammer on bored piles was undertaken and compared to statically tested pile results (Seidel et al[3]). The intent of this program was to show the correlation between the two test methods and provide confidence that HSDT testing on non-uniform piles can provide valid results, and that the sole use of the HSDT method was appropriate for the remainder of the project. Many other projects globally have followed this same approach, demonstrating that HSDT, if performed to a high standard, is suitable for capacity verification of cast in-situ piles.

However, there are limitations and practical difficulties with HSDT testing. These include noise and vibration, hammer size, hammer availability, the need for pile extensions and access requirements. With respect to the hammer weight, generally, the hammer weight required ranges between 1% to 2% of the target test load.

As bored and CFA piles are being pushed to carry higher loads, it is not uncommon to see test load requirements upwards of 20,000kN. This requires hammer weights ranging from 15t to 30t+.

Depending on the ground conditions and the construction technique, the geometry of cast-in-situ piles may or may not be particularly variable. For drilled shafts in stable (stiff or very stiff) clay, the cross-section may be quite uniform. For drilled shafts with temporary or permanent casing, a relatively uniform cross-section can be expected. For drilled shafts in overburden materials such as soft and firm clays and sands, the shaft will generally need to be stabilized, and pile geometry may be less certain. For sockets drilled in strong or massive rock, the socket shape will generally be uniform and predictable. For sockets drilled in weak, weathered or jointed rocks, the socket dimensions may vary considerably due to overbreak during drilling or collapse during or prior to concreting. For concrete injected piles, the pile geometry will not be known in advance. Generally, the poorer the ground conditions and construction control and technique, the more variable the shaft geometry is likely to be.

The geometry of drilled shafts may be established in advance of concreting by such techniques as callipering or acoustic survey (Koden device, SHAPE, TIP – Discussed in later section).

The geometry of drilled shafts may also be established during concreting by monitoring the volume of concrete placed or pumped, and the progressive rise of concrete level in the shaft. CFA piles utilise monitoring systems that are based on pump strokes and instrumentation, which measures concrete pressure in combination with monitoring of pile tip level for a given pile and concrete hose size.
In any case, special effort must be taken to establish the geometry of any cast-in-situ pile that is to be dynamically tested, so that the geometry and resistance effects on the measured stress wave may be reliably differentiated during analysis.

2.1 High Strain Dynamic Testing

HSDT was developed in 1960 (Smith[4]) and made commercially available in the 1970s by Pile Dynamics Inc (PDI[5]). Strain and accelerometer gauges are attached to a pile and capture force/velocity time records for a hammer impact (hammer blow). The information recorded is both the stress-wave from the hammer impact and the reflected stress-waves generated along the pile length (shaft) and from the pile base (toe). For one-dimensional wave dynamics in a slender rod (i.e., a pile) the force travelling downwards is proportional to the velocity multiplied by the impedance, as indicated in equations (1) and (2). This is only true for the downward travelling wave, with no reflected waves and no changes in the impedance.

$$\mathrm{F} = \mathrm{Vz} \tag{1}$$

$$\mathrm{z} = \frac{\mathrm{EA}}{\mathrm{c}} \tag{2}$$

Where: F=force, V=velocity, z=impedance, E=modulus of pile, A=cross sectional area, c=wave-speed of pile.

The hammer impact generates a compression stress wave which enters the pile head and travels along the shaft. As the wave travels downwards, the pile moves downwards and displaces the surrounding ground, ‘slipping’ past the soil at the perimeter. This slipping is referred to as mobilisation, which is a function of displacement vs shear resistance. This mobilised soil resistance is partially reflected as compression waves which are cumulatively added together, causing the initial force and velocity signals to separate (Figure 1). Reflection waves (i.e., waves that do not continue down the length of the pile but reflect back towards the top) are also generated by discontinuities and impedance changes, which may be in tension or compression.

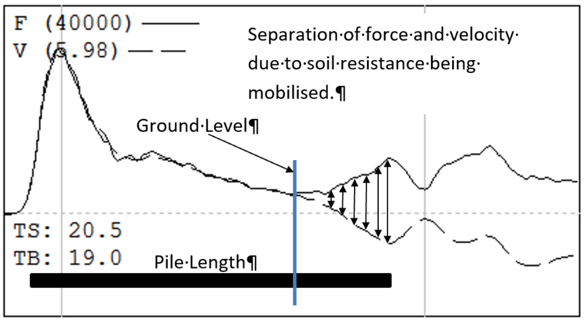

Figure 1. Force and velocity traces from an impact. Showing proportionality up until the ground level, then separate due to the shaft resistance

The greater the shaft resistance acting on the pile, the greater the force/velocity response will separate. An alternate way of viewing the force / velocity response is by using the Wave Up curve (WU) (Figure 2), represented as,

$$\mathrm{WU} = \frac{\mathrm{F-Vz}}{2} \tag{3}$$

This response provides a quick and easy visual indication of the shaft resistance acting on the pile. It also provides a quick assessment regarding any changes in impedance.

An increase in WU represents constant reflections from shaft resistance from the initial downward travelling stress wave. To further demonstrate this, Figure 2 shows the WU response and an indication of the shaft resistance on the pile. As the WU line increases, this infers that shaft resistance on the pile increases. Alternatively, an increase in WU may also represent an increase in pile area, and this will be discussed in further detail in a later section.

It should be noted that this visual assessment of WU relating to shaft resistance only applies to PDA data when shaft resistance reflections are recorded at the gauges during downward movement of the pile. If early unloading occurs (i.e. the pile at the gauges is moving upwards and the pile is unloading) prior to the compression wave reaching the pile toe, then the superposition of the WU and the upward motion of the pile will affect the WU curve.

The WU response should be used as a guide only to indicate the potential shaft resistance. It is not until a more thorough analysis is undertaken to remove dynamic effects, that the static shaft resistance would be determined (i.e., CAPWAP discussed below).

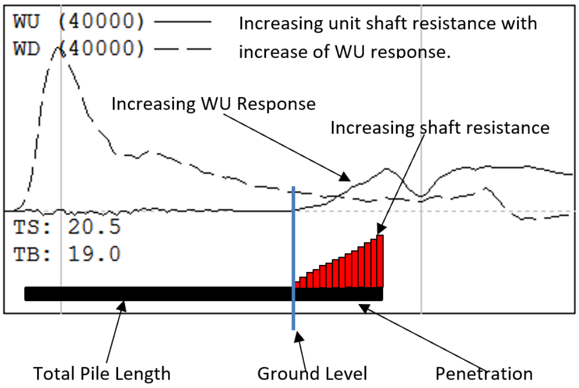

Figure 2. Wave Up (WU) response curve. Effects from an increase in shaft friction

2.2 Signal Matching Analysis

Signal Matching assessment for CAPWAP, developed by Goble et. al. (1979)^6 is generally accepted to be the definitive method on interpreting dynamic pile records. There are other software packages, however, for this paper, CAPWAP has been selected.

CAPWAP 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.

CAPWAP is a numerical analysis based on the one-dimensional wave equation. The pile is divided up into segments (as many or as few as required) where each segment requires material properties and cross-sectional area. Therefore, each segment is represented by impedance and length.

CAPWAP calculates the wave down and wave up values in each segment at times when the waves are either travelling downwards (due to the impact), or upwards (due to reflections from shaft resistance or changes in impedance). Effectively, the total force and velocity for each segment are derived from the net sum (superposition) of the downward and upward waves

Cross-sectional area, elastic modulus, specific weight and pile perimeter are the four input parameters that make up the pile profile. The pile perimeter is only needed for shaft unit resistance calculations. The other three quantities define the standard dynamic pile model.

For uniform piles, the pile top properties are sufficient for the pile profiles over the full length (i.e., one size fits all). For non-uniform piles, the pile profile needs to be specified, as a function of depth, where any one of these four input parameters may change.

For cast-in-situ piles, it is generally the area and perimeter that changes, as we typically assume that the modulus and wave speed are consistent for the concrete over the full pile length. As given in equation (2). the impedance is a function of both pile cross-sectional area and material properties.

However, it is not just the impedance that alters the Force/Velocity relationship, but also external soil resistance that is acting on the segment. The displacement and velocity of each pile segment relative to the soil are the basis for computing the soil resistance forces. The soil model consists of an elasto-plastic spring and linear dashpot (Figure 3). The static and dynamic resistance (Rsk and Rdk) acting on each element is the result of shaft resistance mobilisation under the hammer impact. This also influences the response recorded from HSDT.

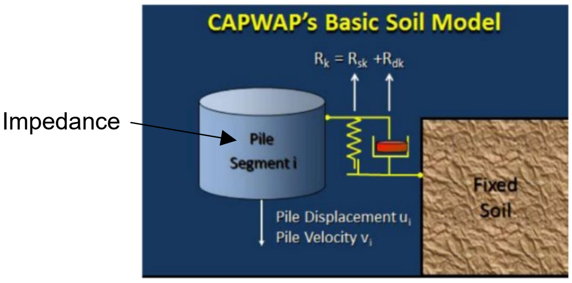

Figure 3. CAPWAP Pile Segment and Soil resistance model (From CAPWAP Background Report 2014)

The data collected from HSDT is imported into CAPWAP where modelling is undertaken by matching the Wave Up response of the pile. Once the pile model has been generated in CAPWAP, the shaft resistance for each pile element is adjusted, along with soil parameters, such as soil quake, damping, loading and unloading parameters. Once the match is complete, the static resistance (mobilised) is determined.

2.3 Comparative Models

To quantify the effects of altering the pile profile with respect to the Wave Up response recorded with HSDT, two pile models have been created, along with two separate soil models.

The analysis for these models will be undertaken using an impact analysis program called GRLWEAP[7], which conducts a predictive Wave Equation Analysis of a Pile (WEAP). It simulates a hammer impact on a pile and calculates the force and velocity x impedance. These are inputs to each pile segment to allow the determination of total resistance, stresses, energy and blow count per meter (or set per blow).

The pile profile for Model 1 has a uniform 1.2m diameter, which represents the design diameter. Model 2 is a non-uniform pile, where the upper profile increases in diameter to simulate an enlarged section due to soft soils/temporary casing or both. The maximum diameter for the enlarged model is 1.65m. Figure 4 presents the radius profile for each of the models.

Comparing the pile section with maximum diameter of 1.65m compared to the design of 1.2m, assuming the modulus and wave speed are equal for both, there is a 45% increase in impedance, an 89% increase in pile area and a 38% increase in perimeter length.

Two shaft resistance models have also been developed to be applied in each pile model. The first includes a constant 'low' shaft resistance over the full penetration length and the second is an increasing shaft resistance with respect to penetration. Figure 5 presents the adopted soil strength models.

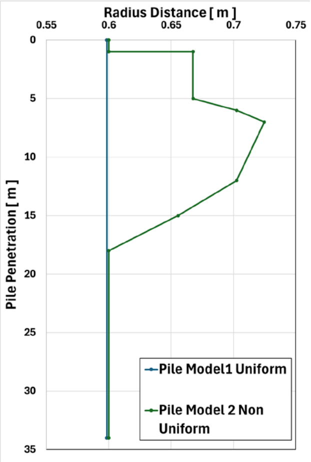

Figure 4. Radius Profile

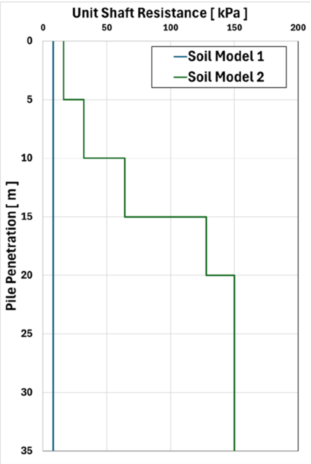

Figure 5. Shaft Resistance Models

The results of the generated Wave Up response from GRLWEAP for each pile model and soil model are presented in Figures 6 and 7 below. For presentation, the profile has been rotated, so that the x axis is penetration, with the focus on penetration length (i.e., toe response omitted).

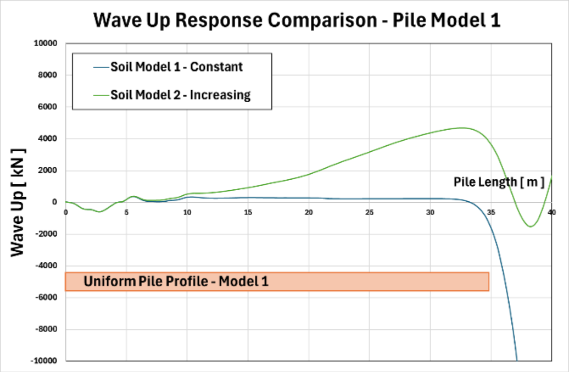

Figure 6. WU Response – Uniform Pile – 2 Soil Models

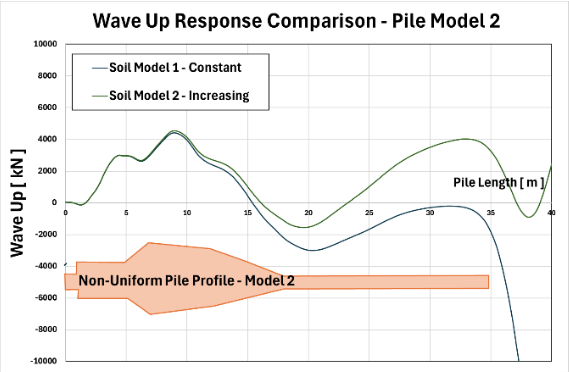

Figure 7. WU Response – Non-Uniform Pile – 2 Soil Models

For the uniform pile, presented in Figure 6, there is a clear difference in the Wave Up response for the two soil models. With low shaft resistance (Soil Model 1), the WU response does not rise, as there is in-sufficient resistance being generated to cause large wave reflections, as well as no changes in impedance (area). With the increasing friction model (Soil Model 2) the WU steadily increases due to increasing shaft wave reflections with depth, even though there is no impedance change. The response for the upper 10m is very similar, as this is where the shaft resistance is relatively similar.

For the non-uniform pile (Figure 7), there is a clear difference in the Wave Up response, observed near the start of the record, where the pile area is larger. The increase in impedance in the upper profile leads to an increase in the WU. This is important, as in the previous example (uniform profile), the WU increase was solely due to the increase in shaft resistance. It is also interesting to note that where the pile profile reduces back to the design diameter, the WU response decreases, which may lead to concerns about pile integrity if the fundamentals of wave mechanics are not properly understood.

For both soil models, with low shaft resistance, the WU response increases then decreases due to the pile sectional changes. As before, there are similarities in the response for Model 2 with respect to both soil models, where the shaft resistance is low. The WU then increases and is 'higher' in bottom half of the pile due the increasing shaft resistance (where the pile section is uniform).

Figure 8 below presents the WU response for the uniform and non-uniform pile, showing the response from Soil Model 2 only.

The difference between the two responses is clear. This demonstrates that the change in pile profile can significantly affect the WU response. If we do not have information to ensure the pile model is geometrically accurate, then how can we generate and accurately assess the shaft resistance acting on a pile?

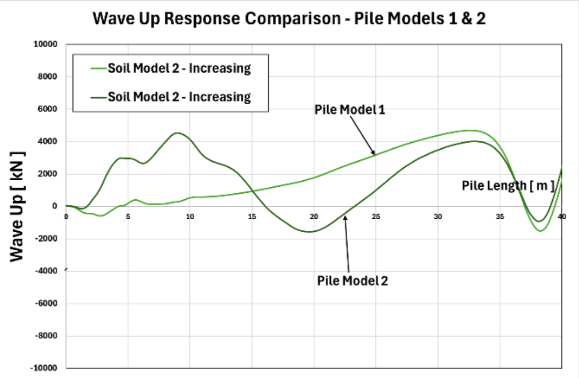

Figure 8. WU Response – Uniform vs Non-Uniform Pile – Soil Model 2 (Increasing)

In the example presented above, it is not justifiable to add shaft friction to model a response that is heavily influenced by the higher impedance in the upper portion of the pile. Hence, the CAPWAP program allows impedance to be added (Impedance can be added or removed without knowing the actual area or material quality). Again, without an accurate pile model, in the authors' opinion, this is an unreliable process. Further, the addition of impedance can be used to create a match where the shaft resistance is consistent to the design, but this may not necessarily be the case.

Without proper consideration, modellers using CAPWAP can potentially model a preconceived shaft resistance profile to 'fit' a design expectation, and then adjust the impedance to suit their already derived opinion. This is modelling the 'wrong pile'.

3 PILE PROFILING

Pile profiling can be undertaken using the following methods:

Open bored piles

- Traditional concrete curves (only really applicable for deep piles with large diameter as there are multiple trucks). Trying to back calculate a pile area when there is less than 10m^3 is difficult, especially when there are only 1 or 2 trucks of concrete.
- Ultrasonic Devices - Using a device lowered down the middle of the pile that sends an ultrasonic signal to the pile perimeter and back to measure the diameter. Some current methods used in the industry are:
    - SHAPE[8] – Shaft Area Profile Evaluator (Pile Dynamics).
    - SONICaliper[9] (LOADTEST/Fugro)
    - KODEN DM602[10] (Koden Electronics)
- There are mechanical examples as well.
- Thermal Integrity Profiling[11] – TIP (Pile Dynamics): from measuring the heat generated during concrete curing, TIP can estimate the cross-sectional area (geometry) for the length of the pile based on the measured temperature and input parameters. This is completed by installing wires with thermal nodes attached every 30cm to the main reinforcement steel of the pile cage. Comparison of individual temperature sensor readings to the average temperature of all sensors at any particular depth, can reveal necks or inclusions (regions that are colder than average), bulges (regions that are warmer than average), variations in concrete cover, and the shape of the shaft and cage alignment.

It should be noted that these three methods have significant differences. Concrete curves collect data at the time of concreting, with measurements typically recorded after each truck load. This makes for a more generalised profile. Sonic calipering methods collect information prior to pile concreting (after the pile hole has been drilled and prior to the cage being installed). TIP collects data on the profile after the concrete has been placed as the temperature from concrete curing is recorded.

Continuous Flight Auger (CFA) piles

- CFA rig instrumentation systems: monitoring systems that are based on either pump strokes or magnetic flow meters in combination with monitoring of pile tip level.
- Thermal Integrity Profiling – TIP (As discussed above).

For CFA piles, the rig instrumentation creates an idealised concrete profile during concreting. However, the data is sometimes questionable, as the concrete volume is measured at a point away from the auger outlet and therefore infers the volume being placed at the auger tip with respect to depth. No consideration is made for concrete volume that 'flights' its way up the auger and is visually seen at the ground level, when the auger is still embedded (sometimes for a few meters or more in the ground). Alternatively, in very soft soils, the concrete may bulge from the weight of concrete and injected pressure below the auger tip, which is also not accurately recorded. With regards to TIP, the cage is inserted after the concrete hole has been cast with 'wet' concrete.

4 CASE STUDY

This case study investigates the testing of a 1,200mm diameter bored concrete pile which was HSDT tested. The total length constructed from top of casing (TOC) was 39.7m. The ground level was 1.8m below the TOC. The temporary segmental casing had a 1,300mm outside diameter (OD) and 1,220mm internal diameter (ID). Polymer fluid was used as a support for drilling due to the high-water table level, soft ground conditions, and wet sand conditions. Regarding the pile construction, there is no detail about how the casing was installed. It is assumed it was advanced prior to internal boring, however, open hole drilling prior to installation of the segments, including drilling beyond the toe may have also occurred.

The generalised soil profile is presented in Table 1. The casing length was 13.7m and was required to penetrate into the underlying sands below the soft clays/peat. The casing was composed of three segment lengths.

Table 1: Geotechnical Profile

Material Description [-]	Thickness- From Ground Level [m]	Soil Strength [-]
Sand	7	Medium Dense
Clay/Peat	4	Soft-Firm
Sand	12	Dense to Very Dense
Sand	4	Medium Dense
Sand	14	Dense to Very Dense

The theoretical concrete volume for the full length to the top of the casing, accounting for the ID of the casing, is 45.4m^3. Accounting for the extraction of the temporary casing with 1300 mm OD, the theoretical concrete volume is 47.6m^3. A concrete curve provided by the contractor is presented in Figure 9.

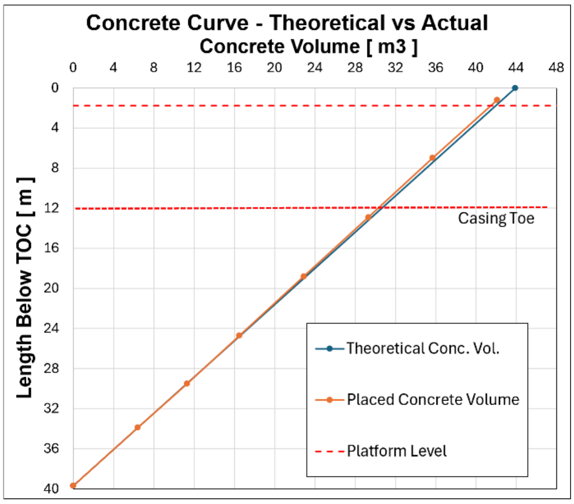

Figure 9. Concrete Curve Case Study

The concrete curve represents the ground below the casing and the cased section only. The curve is very similar to the theoretical curve (i.e., design diameter), which indicates a 'neat' profile, even slightly undersized (steel volume has been accounted for), inferring that the design diameter should be achieved, with no significant pile enlargement or bulges.

The concrete curve does not reflect the true pile profile, as the casing had not yet been extracted. The concrete was placed to the top of the casing, with the tremie left embedded in the concrete. Each casing segment was extracted, and where required, additional concrete was placed in the tremie. The final placed concrete volume was 52.5m^3. This equates to an extra 4.9m^3 of concrete, or an overbreak of 10.2% over the full pile length. This additional 4.9m^3 of concrete is located somewhere over the upper section of the pile where the temporary casing was utilised. Hence, applying the additional concrete to the cased section only, this equates to 31% overbreak over the cased length.

In terms of creating a model for CAPWAP, the additional 4.9m^3 of concrete will affect the impedance and area of the pile, but to what extent and at what depth?

The Wave Up response from the PDA data, for the selected blow, is presented in Figure 10. As the geotechnical profile consists of soft soils for the upper 11m, if the pile has a uniform profile, the Wave Up Response should be relatively 'flat' (see Figure 6). However, the WU response in Figure 10 clearly rises upwards, which indicates that the upper profile must be enlarged, above the design diameter. Hence, the actual pile profile/area must incorporate the additional 4.9m^3 of concrete. Further, we note that the WU response in Figure 10 is very similar to the theoretical response in Figure 7, which is the non-uniform response.

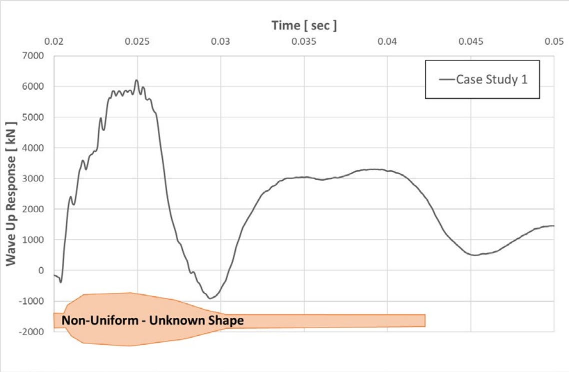

Figure 10. Case Study PDA Wave Up Response

Without knowing the pile shape, trying to create an accurate model without understanding the geometry, or impedance, is very uncertain. This may lead to over or under prediction of the pile compression resistance, or even may infer there is a structural integrity issue.

Within the CAPWAP software, impedance can be adjusted to suit the response. The amount of impedance added (or subtracted) can be compared to the total placed volume, as an increase in impedance is effectively increasing the cross-sectional area, which is then converted to a volume with respect to the length adjusted.

Therefore, without knowing the pile profile, the starting point for CAPWAP is:

1. Input design diameter.
2. Adjust shaft resistance to match the response – if this can be matched (generally, the shaft resistance parameters are modelled to match the expectation of what the expected shear strength parameters should be).

3. Adjust dynamic parameters in CAPWAP.
4. Add Impedance to finalise model and align with the shear strength values used for estimation of shaft resistance.
5. Re-evaluate steps 2 to 4.

The issue with this is that we are assigning the pile geometry at the end of the process, i.e., what should be the first step in the process is the final consideration. This is modelling the 'wrong pile'.

The correct way to undertake a CAPWAP for cast in-situ piles should be as follows:

1. Input design diameter.
2. Alter profile to suit inferred constructed profile.
3. Adjust shaft resistance to match the response.
4. Adjust dynamic parameters in CAPWAP
5. Re-evaluate steps 3 to 4.

Adopting this approach allows for a more accurate determination of the actual resistance mobilised along the shaft of the pile rather than assuming the design shaft values are correct and then adjusting the pile model to suit.

Thermal Integrity Profiling was also completed on this case study test pile. As discussed previously, TIP records the temperature on embedded sensors during the concrete curing process. Analysis is then undertaken using the peak temperature recorded during the curing process to determine the profile of the pile, hence, the results from TIP provide a more accurate profile of the pile after the casing has been removed, unlike the concrete curve assessment, which provides an indication of the profile prior to the casing removal.

To compare the TIP results with the design and construction information of the pile for the Case Study, Figure 11 compares the radius for the pile length. This includes the following:

- Pile Design – Cased 1300mm section upper 13.7m, to represent the casing length, and 1200mm diameter for the remaining length.
- As constructed based on concrete curve and total volume – the additional 4.9m^3 is distributed over the temporary casing section, where the back calculated diameter is 1500mm.
- Data from TIP, where the diameter has been calculated (based on the input data) for the full length.

Figure 11 clearly demonstrates the noticeable difference between the different assumptions/methods for determining where this extra concrete goes. The actual TIP results are very different compared to the design assumptions, and the assumption based on the additional concrete filling the void left upon extraction of the casing.

Further, the TIP output indicates that the pile is enlarged below the cased region. The additional 4.9m^3 appears to have been distributed over the full length of the pile, with a noticeably enlarged profile from approximately 9m to 15m, rather than only over the cased section as would be assumed based on the concrete curve alone.

The reality of these results indicates that the actual profile, compared to an assumed profile for piles constructed in soft soil, is very difficult to predict.

A trial was undertaken by the authors where each author received the PDA raw data, borehole and construction information and were advised to undertake two CAPWAPs, one using the construction details only (i.e. TIP profile cannot be used), and the other using the TIP data for the profile.

The results using the construction information only determined that there was a difference in shaft resistance of +/-10% (1800kN range), calculated from the average of all three results.

However, the results where the TIP profile was used modelled a difference in shaft resistance of +/-5% (900kN range) calculated from the average of all three results.

Overall, the assessment using the TIP profile provided more reliable/consistent estimates for the shaft resistance.

The authors expected a greater range in variation between the shaft resistances and note that the assessed range may be greater if the trial was undertaken by a greater number of CAPWAP users with a broader range of experience and expertise.

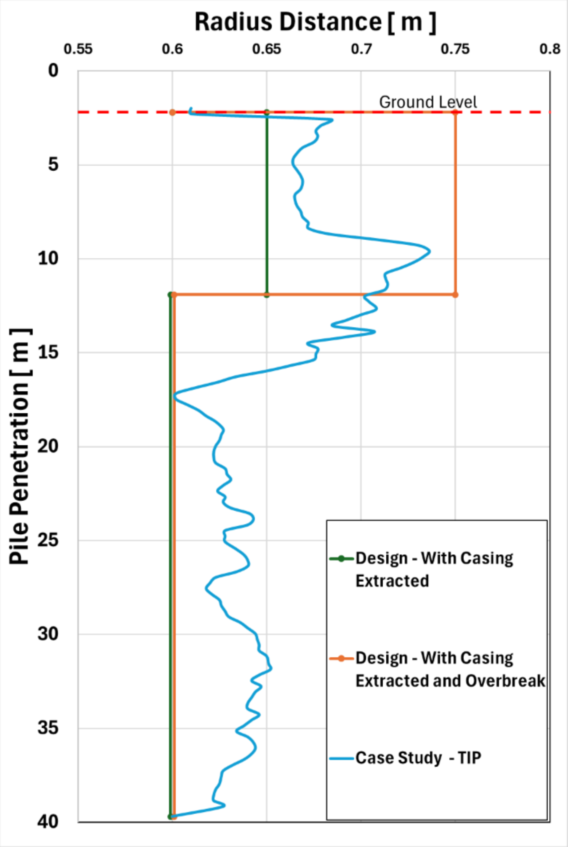

Figure 11. Case Study: Radius Comparison

5 CONCLUSION

This paper presents a comparison of the outcomes of using design vs actual cross-sectional area profiles when undertaking analysis of HSDT.

For cast in-situ piling projects, where test piles are required to verify load requirements and integrity, it is critical to improve our approach to understanding and incorporating the actual profile of tests piles, in order to carry out high quality CAPWAP analysis. This is even more important when we consider the ever-increasing design loads that are being applied to these pile types in practice.

It is evident in the theoretical examples and case study that non-uniform piles, and their variable geometry, can greatly affect the shaft resistance profiles generated in analysis, due to the significance of impedance changes on test data interpretation. More so, the actual shape of a pile, especially when constructed in (or through) soft soils, can be very different when compared to a design pile size. Additionally, the use of temporary casings does not confirm that the pile diameter will be equal to the casing diameter when extracted and can generate overbreak in themselves.

As stated in AS2159-2009 and the CAPWAP User Manual, the use of actual pile profile/geometry will lead to more reliable interpretation and analysis.

All practitioners should be analysing test data using the most accurate profile of the pile that can be interpreted. Where appropriate and practicable, new technologies should be used to assist in this process.

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