The use of pile velocity in verification of untested piles – a sensitivity study

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ABSTRACT

Pile testing is undertaken to confirm that a pile has sufficient geotechnical strength, as per the design intention. In practice, it is common to test only a proportion of the piles. For untested piles, geotechnical strength is usually assessed using bearing graphs or dynamic driving formula based on a combination of energy and movement.

The pile set, as an expression of permanent pile movement, can be measured in a number of ways, such as using traditional pile markings on the pile, survey, or even non-contact high frequency displacement monitoring devices. For untested piles, the energy is generally assumed to be a function of drop height and hammer size, reduced by an energy transfer ratio. Hammer performance, cushion properties, and accuracy of hammer drop height readings are examples of factors that can influence the energy transfer ratio. In turn, this impacts the reliability of the capacity estimate.

As an alternative approach, pile velocity can be used to infer applied force into the pile. Thus, a relationship between geotechnical strength, pile force and static movement (set) can be determined for site-specific verification of untested piles.

This paper investigates the sensitivity of this relationship to dynamic ground parameters (quake and damping), pile impedance and cushion stiffness, using wave equation analyses. It draws on earlier papers discussing the theoretical framework and case study data from high strain dynamic testing.

Keywords: pile testing, displacement monitoring, PDA, construction verification, wave mechanics

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 ground resistance. Pile testing is undertaken to confirm that the pile has sufficient geotechnical strength and can significantly reduce the uncertainty of the pile-soil resistance behaviour.

However, each test has direct relevance only to the individual pile which is tested. In an earlier paper Seidel and Denes (2021) argue that, for driven piles, the results of dynamic pile tests are to be synthesized into a locally-evidenced and locally targeted dynamic formula, which allows for verification of the (static) geotechnical resistance R_n, based on pile driving behaviour.

The advantage of (site-specific) dynamic formulae is that they can serve as a practical means of pile verification during construction. As an alternative, wave equation analyses can provide site-specific acceptance criteria. Such acceptance criteria will generally be expressed in hammer drop height, pile set and temporary compression. As such, it expresses the relationship between energy (hammer drop height), movement (set and temporary compression) and capacity (static geotechnical resistance). This relationship is referred to as the energy-capacity-movement (ECM) relationship. Figure 1 shows an example of a typical ECM relationship.

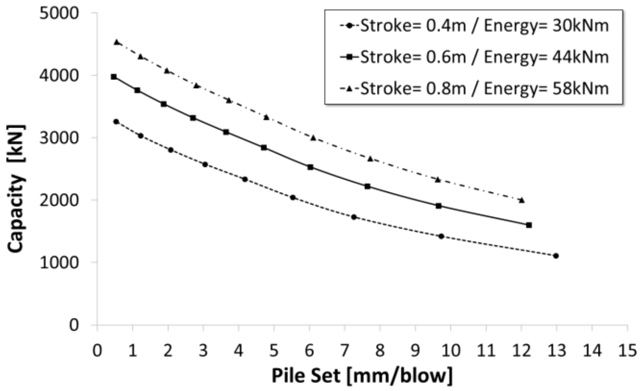

Fig. 1. Example ECM relationship showing geotechnical capacity against pile set for different amounts of transferred energy.

However, both dynamic formulae and wave equation based criteria are still sensitive to the assumptions made on energy transferred into the pile by the driving hammer. Factors such as hammer efficiency, maintenance, alignment and hammer cushion all influence the actual energy transferred to the pile. The high variability in hammer performance and energy transfer can lead to very significant scatter in predicted geotechnical resistance (Allin, 2015; Seidel, 2015; Flynn and McCabe, 2016).

Denes et al (2021) discuss an alternative approach, which uses the force applied at the top of the pile, instead of assumed energy. This force can be inferred from measured pile velocity, using either high frequency displacement monitoring or from accelerometers attached to the pile. The approach uses site-specific force-capacity-movement (FCM) relationships, which are derived based on dynamic test results, in conjunction with wave equation modelling of pile driving.

This paper investigates the sensitivity of this relationship to dynamic ground parameters quake and damping, pile impedance, and cushion stiffness, using wave equation analyses. This paper focuses on concrete driven piles to allow the investigation on the effects of the pile cushion and pile modulus. It is the experience of the authors that the use of timber cushions has a significant impact on energy transfer in these pile types (Seidel, 2015).

2 FORCE-BASED APPROACH

The force-based approach, as an alternative to the energy-based approach, was first discussed and presented by Seidel (2018) and further detailed by Denes et al (2021).

Initially, a relationship between force, capacity and movement (pile set) is established using wave equation models, on the basis of the ground model, pile type and estimates of dynamic behavior, such as quake and damping. This relationship can be graphically presented as a graph, similar to a bearing graph, plotting the capacity/force ratio against the pile set (see Fig. 2).

Once the initial theoretical relationship is established, dynamic pile tests with associated signal-matching are conducted and the test results are used to validate and, if needed, calibrate the model (see Fig. 2). The wave equation data in Fig. 2 is based on the same models as Fig. 1.

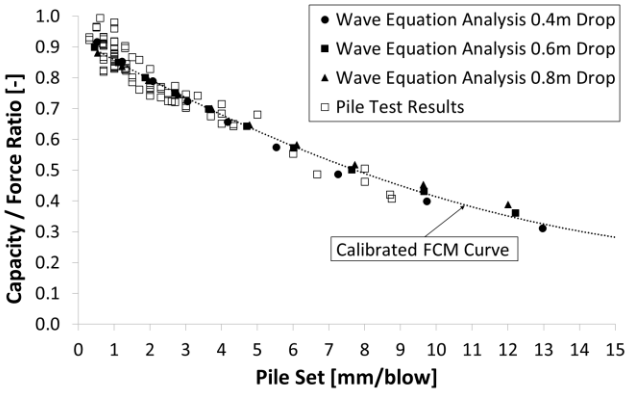

Fig. 2. Calibrated FCM curve, including pile test results. This model is used as the reference for the sensitivity analysis.

For untested piles, pile force is inferred from pile velocity, based on the principles of one-dimensional wave theory, which demonstrates that at the exact moment of hammer impact, and before any reflection waves arrive, the pile force and velocity at the pile top are proportional. The relationship at this time is:

$$F = v \cdot Z \quad (1)$$

Where F is pile top force, v is pile top velocity and Z is the pile impedance, with:

$$Z = EA/c \quad (1)$$

In which E is the pile elastic modulus, A is the cross-sectional area and c is the pile wave-speed.

The graph is then used to estimate the capacity for the untested piles from the ratio of the capacity to force, where the force is calculated from velocity.

Any ongoing pile test results are to be incorporated in the model as pile installation progresses.

3 SENSITIVITY ANALYSIS

The purpose of this paper is to investigate the sensitivity of the force-based approach to:

- Hammer drop height;
- Quake;
- Damping;
- Pile impedance, and;
- Cushion properties.

Wave equation analyses using GRLWEAP were conducted to establish capacity/force/set relationship, using a range of the above parameters.

In order to investigate the sensitivity to the above parameters, a reference, or baseline, model must be established. For the purpose of this paper, we have used a correlated capacity/force/movement relationship that has been derived from an actual project (Fig. 1).

The project comprised of 78 no. driven precast concrete piles (400 x 400 mm^2), all of which were dynamically tested. Back analyses were conducted on all test piles.

The model properties of the fitted curve are given in Table 1. In addition to this, Table 1 shows the lower bound and upper bound values that were selected for the purposes of the sensitivity analysis.

Table 1. Parameter values for reference model and sensitivity analysis.

Parameter	Reference	Lower bound	Upper bound
Hammer drop height (m)	0.6	0.4	0.8
Shaft quake (mm)	2.5	1.5	3.5
Toe quake (mm)	8.0	5.0	11.0
Shaft damping (s/m)	0.65	0.3	1.0
Toe damping (s/m)	0.5	0.3	1.0
Pile modulus (GPa)	39	34	47
Cushion stiffness (MPa)	800	200	1600

Fig. 4 shows the derived FCM curves for hammer drop height. As discussed previously, hammer drop height is commonly used as a proxy for energy in the driving formulae and bearing graphs based on the energy-capacity approach.

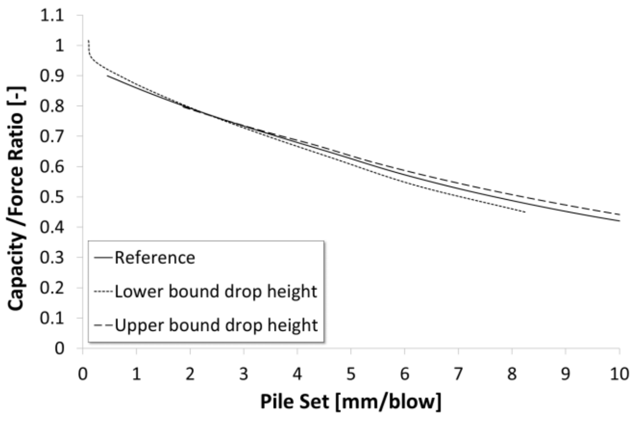

Fig. 4. Capacity/force ratio against pile set for range of hammer drop heights.

The force-based approach is expected to be generally insensitive to hammer drop height, since the capacity is estimated using a force-capacity ratio, which is confirmed by the analysis.

It should be noted that it has been assumed that hammer drop height does not influence hammer efficiency. In practice, notably with rope-lifted drop, the efficiency tends to reduce with increased drop height, due to e.g. friction in the winch and resistance due to misalignment of the hammer in a dolly.

Fig. 5 shows the sensitivity of the derived FCM curves to shaft and toe quake.

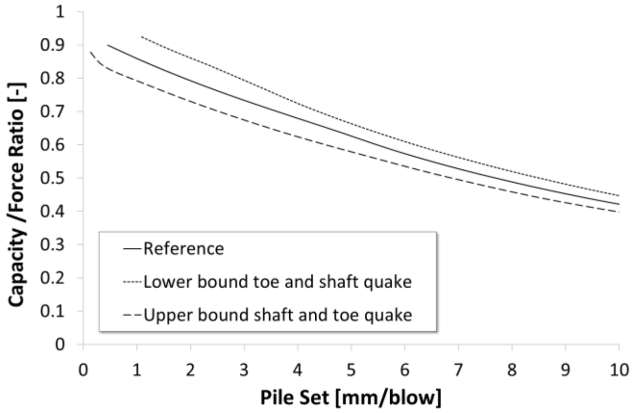

Fig. 5. Capacity/force ratio against pile set for range of quake values.

Quake represents the displacement over which the soil resistance is elastic and is inversely related to soil stiffness. With larger quake values, the dynamic portion of soil resistance to driving is larger. Therefore, a lower capacity/force ratio is expected at the same set.

Fig. 6 shows the sensitivity of the derived FCM curves to shaft and toe damping as per the standard Smith approach.

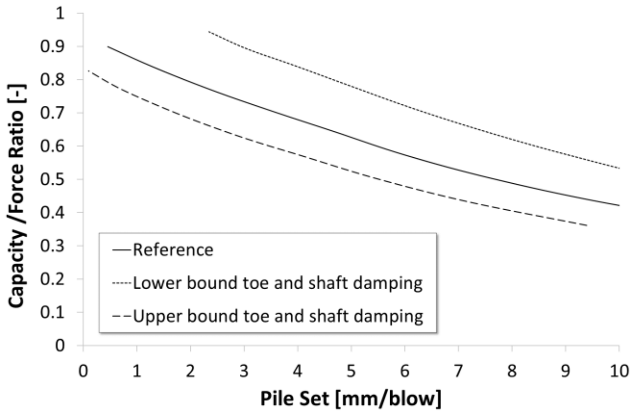

Fig. 6. Capacity/force ratio against pile set for range damping values.

With larger damping values, the dynamic portion of soil resistance to driving is larger. Therefore, a lower capacity/force ratio is expected at the same set.

The upper and lower bound values adopted for the dynamic parameters quake and damping are based on a typical range of values observed in the industry through results of high strain dynamic pile testing. Values outside of this range may also be possible.

Fig. 7 shows the sensitivity of the derived FCM curves to the elastic modulus of the pile. The lower bound, reference and upper bound values selected correspond to expected values for 45, 60 and 85 MPa concrete, which are typical values for the Australian piling industry.

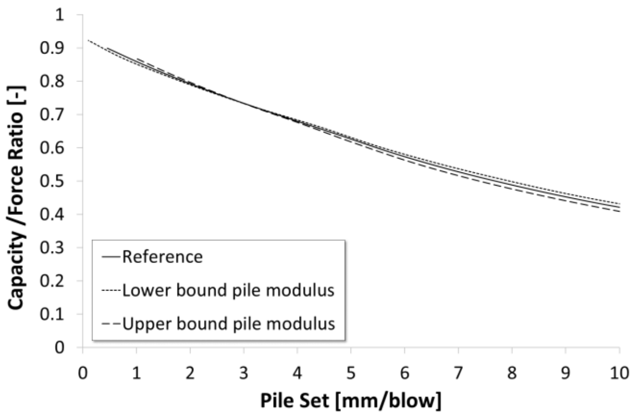

Fig. 7. Capacity/force ratio against pile set for range of pile elastic modulus values

As can be seen in formula (1), pile impedance, which dictates the proportionality of force and velocity at time of impact, is influenced by elastic modulus of the pile. However, the relationship between the pile force, capacity and movement is not influenced by the elastic modulus.

This does not mean that the FCM approach as a whole is insensitive to pile impedance. After all, correct assumptions on about the elastic modulus are to be made when relating force to velocity. This requires a good understanding of factors influencing pile modulus, such as age and concrete strength. These can also be indirectly estimated during dynamic testing of test piles and applied to the untested piles.

Fig. 8 shows the sensitivity of the derived FCM curves to pile cushion modulus. The cushion thickness (50 mm) and stiffness in the reference model have been derived from onsite observations and back analysis results.

In practice, cushion properties can vary between cushions due to material properties, thickness, material etc. In addition to that (timber) cushion properties will also change during driving, due to the continuous impact on the cushion.

In the experience of the authors, cushion thickness can reduce by 30-50%. The type of timber, the location (within the world) and manufacturing process all contribute to the initial and final stiffness. Commonly recommended values for stiffness of a plywood cushion are 200 MPa for a new cushion, against 500 MPa for a used cushion with no correction for thickness (PDI, 2020).

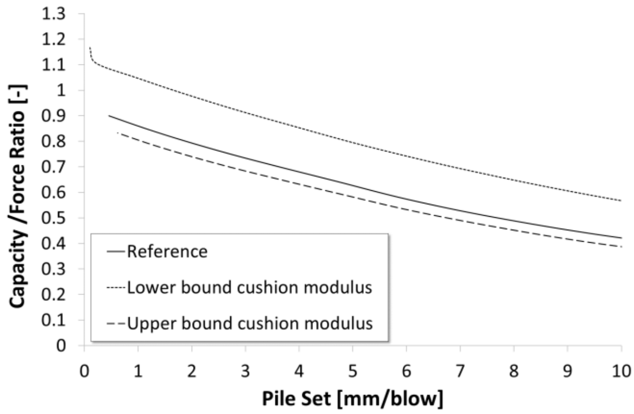

Fig. 8. Capacity/force ratio against pile set for range of pile cushion moduli.

With respect to observed wave analysis comparisons using force and velocity, for a used cushion (thinner and stiffer than a new one), the shape of the impact wave will be steeper and higher. Conversely, a new cushion will lead to an impact wave with a longer duration, and with lower peak force and velocity. Total energy transferred into the pile is expected to be almost the same (although some more damping will occur in a new cushion).

To correct for the increased peak force, the capacity/force curves (Fig. 8) shift down for a stiffer and/or thinner cushion and up for a thicker and/or less stiff cushion.

4 CONCLUSIONS

A sensitivity analyses was conducted to investigate the sensitivity of the force-based approach to quake, damping, pile impedance and cushion properties, for concrete driven piles.

The FCM relationship is insensitive to hammer drop height, under the assumption that there is no effect from drop height on hammer efficiency.

The method is somewhat sensitive to selected quake values and very sensitive to damping values. This reinforces the importance of 1) using a ground model that is locally-evidenced as the basis and 2) calibrating the ground model with the results of dynamic pile tests.

Pile modulus which dictates the proportionality of force and velocity at time of impact, is influenced by elastic modulus of the pile, but the relation between the pile force, capacity and movement is not influenced by the elastic modulus.

The FCM relationship is also very sensitive to cushion properties (thickness and stiffness). Cushion properties can vary between cushions, but will also change significantly during driving. This is a parameter that is difficult to control in the field. The sensitivity of the method to these properties shows that caution must be taken when applying the method on concrete driven piles. Of course, this is less relevant when driving steel piles.

This limitation could be managed by replacing cushions towards end of drive with new cushions, with known properties. This should be done for all piles, including test piles. An alternative could be to use constant-stiffness cushions.

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