Energy Transfer Ratio for Hydraulic Pile Driving Hammers

Kevin N. Flynn[1], Bryan A. McCabe[2]
[1]AGL Consulting, Sandyford, Dublin 18, Ireland
[2]College of Engineering & Informatics, National University of Ireland, Galway, Ireland

Email: kevin.flynn@agl.ie, bryan.mccabe@nuigalway.ie

ABSTRACT: The ability of hydraulic pile driving hammers to overcome energy losses during freefall enables a greater proportion of the impact energy to be transferred to the pile in comparison to diesel hammers. This percentage, termed the energy transfer ratio, is not routinely measured in practice however, and there is an element of uncertainty regarding appropriate energy transfer ratios to assume in driveability analyses. In light of such uncertainties, the energy transfer ratios of four- and five-tonne hydraulic hammers were assessed during installation of driven cast-in-situ piles at several sites in the United Kingdom. The piling rigs were fitted with instrumentation which enabled measurement of the hammer velocity (and hence kinetic energy) at impact for each blow during installation, with the corresponding magnitude of energy transferred to the closed-ended steel installation tube ascertained using a Pile Driving Analyser. The results of the study showed that energy transfer ratios were strongly dependent on the hammer drop height, with transfer ratios of 95% advocated by the pile hammer manufacturer only achievable when a drop height in excess of about 600 mm was used. As such, lower energy transfer ratios may need to be considered in driveability predictions for these pile types (i.e. steel or DCIS piles) if lower drop heights are used during driving. Further research is required to substantiate limited data suggesting that soil type may also be influential.

KEY WORDS: Foundations; Piling; Driving; Hydraulic; Hammer; Energy;

1 INTRODUCTION

The installation of a displacement pile to a required penetration typically necessitates the application of large forces to the pile head. For these pile types, impact driving remains the most common method of applying such forces, although vibratory [1] and jacking methods [2,3] are becoming increasingly popular, particularly in urban areas where noise and vibration tend to be restricted.

The principle of impact pile driving involves imparting a force on the pile head using a large mass, typically termed a ram, which falls vertically from a predetermined height. The potential energy of the hammer before freefall can be readily calculated. The magnitude of energy transferred to the pile during driving is routinely measured using a Pile Driving Analyser (PDA). These two quantities are commonly used by hammer manufacturers to classify hammer performance; the energy transferrable to the pile is expressed as a proportion of the energy corresponding to the maximum drop height, known as the rated energy. However, the 'intermediate' energy state at impact is less certain and is rarely, if ever, measured in practice. This is unfortunate given that it is the ratio of the energy at impact to the energy transmitted to the pile that is the more fundamental indicator of driveability.

In light of the paucity of such data, a systematic study of the energy transfer process relevant to the installation of a number of driven cast-in-situ (DCIS) piles using hydraulic hammers is presented in this paper. Examples of structures in Ireland that have been successfully supported on DCIS piles are the Sequence Batch Reactors (SBR) at Ringsend Wastewater Treatment Plant in Dublin [4]. All piles referred to in this paper were installed by Keller Foundations at sites in the United Kingdom. Unlike previous studies of energy transfer ratio, the hammer velocity (and hence kinetic energy) at impact was measured for each blow during driving using instrumentation fitted to the piling rigs. The approach is analogous to that carried out for energy correction of the Standard Penetration Test [e.g. 5].

2 BACKGROUND

2.1 *Hammer Efficiency*

The ideology of pile driving involves impacting the pile head with a ram of mass m, which has fallen vertically from a predetermined drop height h. The potential energy of the ram immediately prior to release is given by:

$$E_{potential} = mgh \quad (1)$$

At impact, the hammer will be travelling at a velocity v_{impact}, with kinetic energy given by Equation 2:

$$E_{impact} = \frac{1}{2} m v_{impact}^2 \quad (2)$$

If no energy losses occur in the system during hammer freefall, the kinetic energy at impact would be equivalent to the potential energy, i.e. $v_{impact} = (2gh)^{0.5}$. However, losses invariably occur due to friction, ram misalignment and preadmission within the hammer, for example, resulting in a kinetic energy at impact which is lower than the potential energy prior to hammer release. The reduction in energy is typically quantified by the hammer efficiency according to Equation 3:

$$\eta_{hammer} = \frac{E_{impact}}{E_{potential}} \quad (3)$$

For hydraulic hammers, the additional acceleration of the ram during downfall (over and above that due to gravity) is exploited to overcome much of the energy losses outlined previously, rendering hydraulic hammers more efficient than traditional air, steam and diesel impact hammers in this regard. As a consequence, a value of $\eta_{hammer} = 0.95$ is typically assumed in driveability analysis programmes [6].

The impact energy E_{impact} of the pile driving hammer was derived using the two timing signals technique in which the velocity of the hammer during freefall is measured using a pair of sensors located at the top of the hammer assembly. A Keller Foundations piling rig is shown in Figure 1 with the sensors circled on the photograph; these are mounted on a steel bracket placed ~50 mm vertically apart. During hammer freefall, the time taken for the hammer rod to transit this distance is measured by the sensors and the velocity at the bottom sensor location is computed. By accounting for the additional distance travelled between the bottom sensor and the level of impact, v_{impact} can be obtained using the equation of motion, and E_{impact} calculated in turn from Equation 2. The drop height is then back-figured using Equations 1 and 3. Further commentary on the rig instrumentation and its applications, as deployed by Keller Foundations, is given by Egan [7,8].

Figure 1. Pile hammer instrumentation for measuring hammer velocity prior to impact (courtesy of Keller Foundations, UK)

2.2 Transferred Energy

Dynamic pile testing is now routinely used for the verification of pile capacity as a complement to traditional static testing, with various proprietary software programs (e.g. GRLWEAP, TNOWAVE and PDPWAVE) available to provide predictions of pile resistance using signal matching techniques. Stress waves generated within a pile (or a pile tube in the case of DCIS piles) after each hammer blow are characterised using diametrically-opposite pairs of strain gauges and accelerometers attached within 1 m or 2 m of the pile head or top of the drive tube (see Figure 2).

The instrumentation and recording unit are collectively referred to as a Pile Driving Analyser or PDA. The energy transferred to the pile is then calculated using Equation 4 [e.g. 9]:

$$E(t) = \int F(t)V(t)dt \quad (4)$$

where F(t) and V(t) are the force and velocity magnitudes at time t after hammer impact respectively. The maximum energy generated in the pile during this time (corresponding to an individual blow) is referred to as EMX.

Figure 2. Pile Driving Analyser: an accelerometer and strain gauge pair for measuring transferred energy on a DCIS pile tube (top), data acquisition unit (bottom)

2.3 Energy Transfer Ratios

As alluded to in the introduction, the energy at impact E_{impact} is not routinely measured in practice. In this instance, driveability analyses typically assign the maximum potential energy of the hammer to the E_{impact} term, referred to as the rated energy E_{rated}. This leads to the definition of the rated energy transfer ratio (ETR_{rated}), calculated according to Equation 5:

$$ETR_{rated} = \frac{EMX}{E_{rated}} \quad (5)$$

However, as impact hammers tend to perform at drop heights considerably less than the maximum available, and hammers are not fully efficient (Section 2.1), it is worthwhile to assess the true energy transfer ratio (ETR) as a function of drop height. ETR falls below unity due to noise and heat generated at impact and is calculated as follows:

$$ETR = \frac{EMX}{E_{impact}} \quad (6)$$

The ETR ratio is a more fundamental indicator of pile driveability than ETR_{rated}. A driveability study by Hussein et al. [10] on prestressed concrete piles (with plywood hammer and pile-top cushions) is an example of a study that considered the effect of drop height on ETR_{rated}. The authors believe that the research reported here is unique as it allows determination of the actual ETR.

3 EXPERIMENTAL PROGRAMME

The energy transfer data herein pertain to five separate Keller Foundations DCIS sites in the United Kingdom, the locations of which are illustrated in Figure 3. The ground conditions at Shotton, reported by Flynn et al. [11], comprise uniform medium dense to dense marine sand to depths in excess of 10m. The stratigraphy at the remaining sites tended to be variable, typically comprising layers of soft clay overlying loose to very dense sands and gravels. Cone Penetration Test (CPT) profiles for the five sites are shown in Figure 4 from which it can be seen that a broad spectrum of driving conditions were encompassed by the study. Further details of the ground conditions at each site are provided in Flynn [12].

Figure 3. Test site locations

The energy transfer database is presented in Table 1, which summarises the locations of the sites, pile reference, length, diameter, average drop heights and total number of blows imparted. It can be seen that a wide range of drop heights are represented. While the database contains a total of 12 piles, 8 of these are from the Tilbury site, and therefore some bias of the results towards this site may be expected.

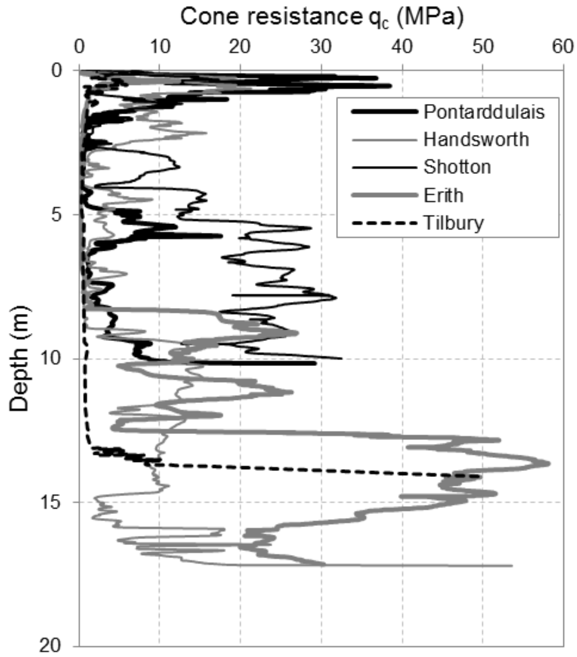

Figure 4. CPT profiles at test sites

All piles were installed using Junttan's HHK A-Series hydraulic hammers with a maximum drop height of 1.2 m. A four tonne HHK4A hammer was used to install the DCIS piles at Pontardulais and Handsworth, with the five tonne HHK5AS hammer used at the remaining sites. Summary technical details of these two hammers are provided in Table 2 [13].

Table 1. Energy transfer ratio database

Site	Pile Ref.	Diameter (mm)	Length (m)	Average drop height (mm)	Hammer Blows
Pontarddulais	P1	320	8.50	240	95
Shotton	S1	320	5.75	450	157
Handsworth	H1	285	7.50	400	259
Erith	S594	320	12.10	370	223
Tilbury	C7	610	14.25	600, 820	1025
Tilbury	N21	610	14.25	580, 840	1087
Tilbury	N42	610	14.30	610, 840	1235
Tilbury	SE6	610	14.75	630, 820	1136
Tilbury	SE8	610	14.80	415, 550, 790	1221
Tilbury	SE16	610	14.75	624, 875	932
Tilbury	SE17	610	14.75	560, 805	1193
Tilbury	SE18	610	14.75	600, 820	1214

Table 2. Details of Junttan hammers used in this study [13]

Specification	HHK4A	HHK5AS
Ram mass (kg)	4000	5000
Total mass [1] (kg)	7100	8400
Max. drop height (m)	1.2	1.2
Max. energy (kNm)	47	59
Blows per minute	40-100	40-100

[1] including A-Type drive cap for metal tubes

The installation process for a DCIS pile is described by Flynn and McCabe [14]; it is analogous to that for a closed-ended steel pile, comprising a 20 mm thick steel tube fitted with a sacrificial circular steel plate at the base to prevent ingress of soil and groundwater during the driving process. No pile cushions were used between the tube head and hammer assembly. The tube is subsequently filled with concrete before being withdrawn, although this stage is not relevant to the driveability study. Monitoring was undertaken on the majority of hammer blows during each pile drive, with the exception of Handsworth where PDA measurements were obtained for the final 50 blows only (of the 259 in total).

4 RESULTS

The variation in drop height is shown in Figure 5, back-figured by the rig instrumentation as described in Section 2.1, with blow number during the installation of each of the test pile in Table 1. Hammer drop heights at Pontarddulais, Shotton, Handsworth and Erith, ranged between 250 and 500 mm, and typically remained constant throughout each pile drive. At Tilbury, the driving sequence necessitated the use of two drop heights, comprising 400 to 600 mm for the initial 13 m, increased to between 750 and 900 mm below this depth during penetration in dense sandy gravel.

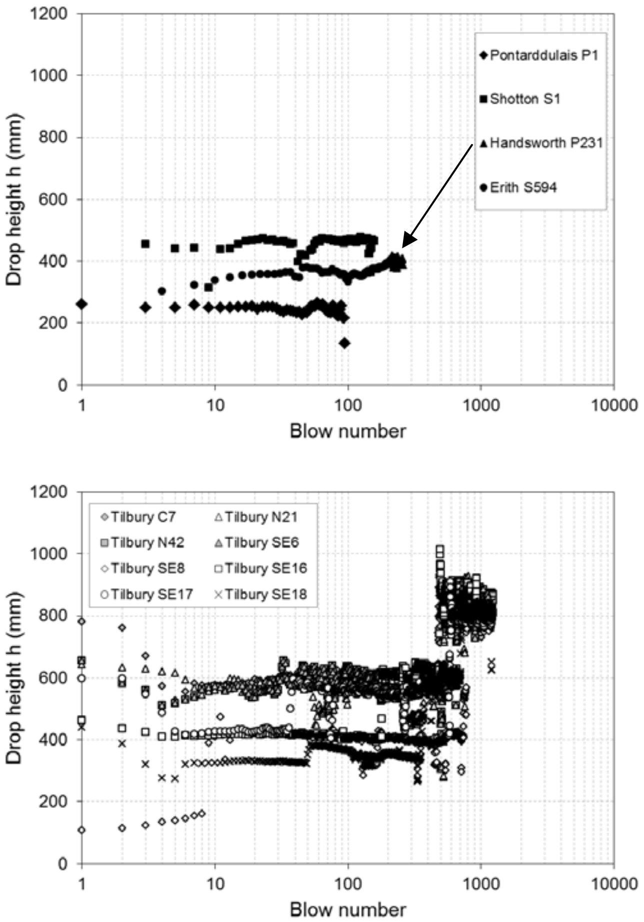

Figure 5. Variation of drop height with blow number for piles at (a) Pontarddulais, Shotton, Handsworth and Erith, and (b) Tilbury.

As mentioned in Section 3, each test pile was also monitored dynamically during driving using a PDA. All PDA testing reported in this paper was performed by the same pile testing company. Figure 6 shows an example of the energy data for Pile S594 at Erith. The impact energy and corresponding transferred energy (EMX) were assessed for each hammer blow of the pile drive.

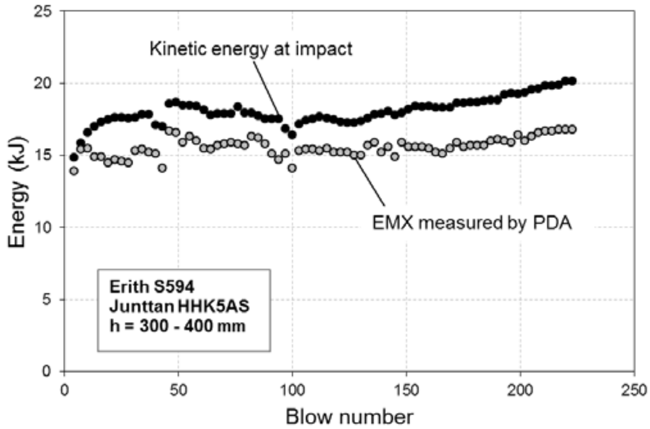

Figure 6. Comparison of impact and transferred energies during installation of Pile S594 at Erith

The variation in transferred pile energy EMX with the kinetic energy at impact is shown in Figure 7 for all 12 DCIS piles in the database. A linear trend is obtained, although the variability appears to increase with increasing drop heights (and hence impact energy).

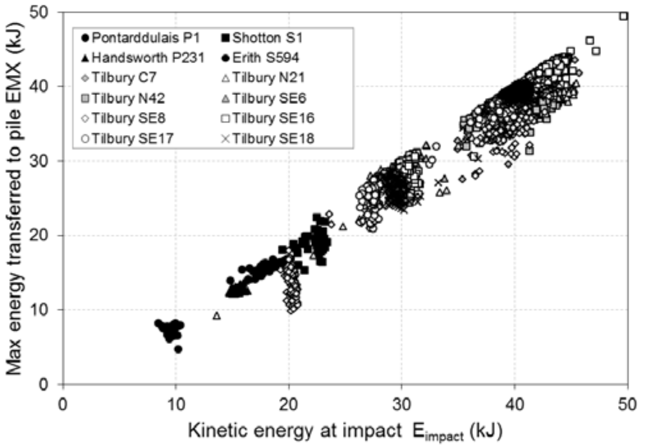

Figure 7. Relationship between kinetic energy at impact and energy transferred to pile

The energy transfer ratio (ETR) was calculated for each hammer blow using Equation 6. Due to inherent variability in the measured data, averaging was applied both to the drop heights and energy transfer ratios. The resulting variation in average energy transfer ratio ETR_{avg} with average drop height h_{avg} is shown in Figure 8. Note that the vertical range bars represent plus or minus one standard deviation about the average energy transfer ratio. It is apparent that:

- The average energy transfer ratio increases with drop height, ranging from ~75% at drop heights of 250 mm to over 90% when h is 600 mm or more.
- The variability in energy transfer ratio tends to reduce somewhat with increasing drop height.
- Pile SE8 at Tilbury had a considerably lower transfer ratio (~65%) in comparison to other piles at Shotton, Handsworth and Erith for a drop height of ~400 mm.

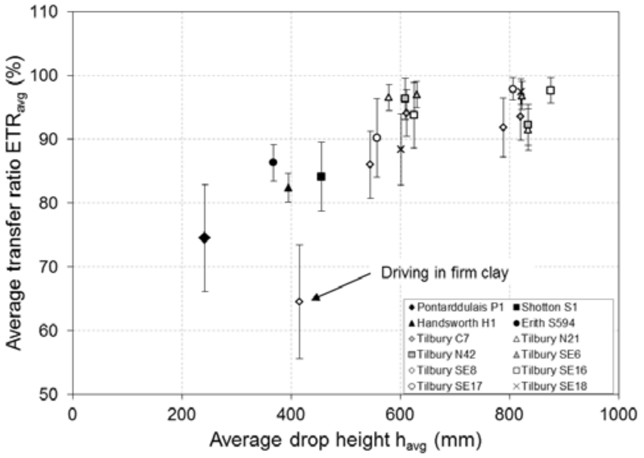

Figure 8. Variation in measured energy transfer ratio with drop height

Unlike the other piles at Tilbury, dynamic monitoring for Pile SE8 was initially carried out while the pile was penetrating a layer of firm clay above the sandy gravels and drop heights of about 400 mm were used within this stratum. It is therefore possible that the ground conditions may have a significant effect on the reduced energy ratio noted in this case. Further investigation of this effect is warranted, although the dearth of driveability data in firm clay in the database in Table 1 precludes such a study from being undertaken at present.

Hammer manufacturers advocate that energy transfer ratios of 95% are routinely achieved during driving of steel piles or casings without hammer cushions. Based on the data illustrated in Figure 8, it is apparent that such energy transfer ratios are only achievable for drop heights in excess of 600 mm. As such, lower energy transfer ratios may need to be adopted in driveability predictions for these pile types (i.e. steel or DCIS piles) if lower drop heights are used during driving.

As discussed previously, the energy at impact E_{impact} is not routinely measured in practice and driveability programs quote the energy transfer ratio as the transferred energy as a proportion of the maximum rated energy of the hammer. In order to facilitate comparison with the limited studies of energy transfer ratio in the literature, the transferred energies measured for each test pile in Table 1 have been normalised by the corresponding hammer rated energy (as given in Equation 6) and plotted against hammer drop height in Figure 9, with the vertical range bars representing plus or minus one standard deviation about $ETR_{rated,avg}$. A linear relationship is observed. In contrast, typical $ETR_{rated,avg}$ values of 30-40% were observed in the aforementioned study by Hussein et al. [10] which were relatively independent of drop heights in the range 2 ft. (≈610 mm) to 15 ft. (≈4570 mm). This comparison highlights the dangers of applying $ETR_{rated,avg}$ values to piling scenarios other than those for which they were measured.

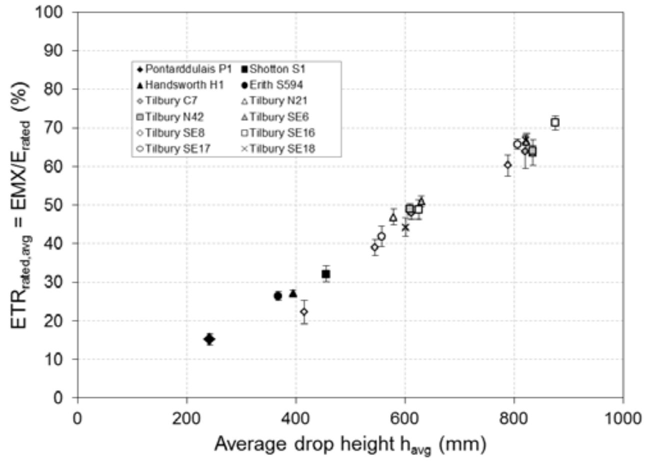

Figure 9. Variation in rated energy transfer ratio with drop height.

Finally, the magnitude of energy loss after hammer impact was determined as the difference between E_{impact} and EMX. As shown in Figure 10, energy losses ranged from 1 kJ to 6 kJ (and the vertical standard deviation bars indicating large variability) with no clear trend with drop height apparent. This suggests that the energy losses after impact may be independent of drop height. Furthermore, the magnitude of such losses represent a smaller proportion of the impact energy as the drop height increases, leading to the greater energy transfer ratios shown in Figure 8.

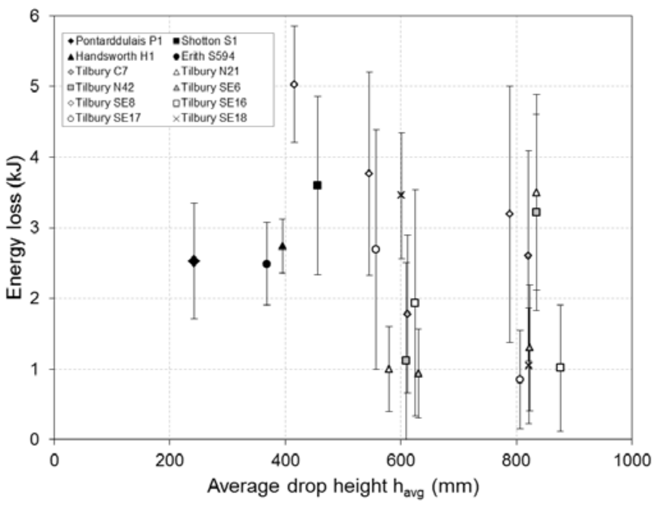

Figure 10. Variation in absolute energy loss with hammer drop height

5 CONCLUSIONS

This paper provides an assessment of the energy transfer ratio of hydraulic impact hammers during the installation of driven cast-in-situ piles at several sites in the United Kingdom. The impact energy was derived using the two timing signals technique, with a wide range of hammer drop heights analysed. The results of the study revealed the following:

- Energy transfer ratios (ETR) ranged from 65% and 95% during driving and were strongly dependent on hammer drop height.
- The ETR of 95% advocated by the pile hammer manufacturer was only achievable when a drop height in excess of about 600 mm was used. Increased variability in ETR occurred as drop height reduced.
- The ground conditions may have a significant effect on the energy ratio for a given drop height, with the ETR for pile in driven in firm clay ~20% lower than that observed for piles driven in sandy gravel.

As such, lower energy transfer ratios may need to be considered in driveability predictions for these pile types (i.e. steel or DCIS piles) if lower drop heights are deployed.

ACKNOWLEDGEMENTS

The authors wish to acknowledge Keller Foundations for sponsoring a comprehensive programme of DCIS pile testing, of which this driveability study is part. The first author was sponsored by the College of Engineering and Informatics Fellowship and University Foundation Bursary during his doctoral studies at NUI Galway.

REFERENCES

[1] Rausche, F. and Beim, J. (2012), 'Analyzing and interpreting dynamic measurements taken during vibratory pile driving', *Proceedings from Testing and Design Methods for Deep Foundations/IS-Kanazawa*, Kanazawa, Japan, 123-131.

[2] Lehane, B.M., Pennington, D. and Clarke, S. (2003), 'Jacked end-bearing piles in soft alluvial sediments of Perth', *Australian Geomechanics Journal*, Vol 38, Issue 3, 123-135.

[3] White, D.J. and Deeks, A.D. (2007), 'Recent research into the behaviour of jacked foundation piles', *Advances in Deep Foundations*, Yokosuka, Japan, 3-26.

[4] Suckling, T. (2003). 'Driven cast in situ piles, the CPT and the SPT – two case studies', Ground Engineering, Vol. 36, Issue 10, 28-32.

[5] ASTM D4633-10 (2010) 'Standard Test Method for Energy Measurement of Dynamic Penetrometers', *ASTM International*, West Conshohocken, PA.

[6] Rausche, F. and Klesney, A. (2007), 'Hammer Types, Efficiencies and Models in GRLWEAP', *PDCA 11th Annual International Conference and Exposition*, Nashville, USA, 97-118.

[7] Egan, D. (2013), 'The load capacity of driven cast-in-situ piles derived from installation parameters', *Installation Effects in Geotechnical Engineering*, Rotterdam, The Netherlands, 99-103.

[8] Egan, D. (2014), 'Real-time validation of driven cast-in-situ piles', *Proceedings of International Conference on Piling and Deep Foundations,* Stockholm, Sweden, 65-72.

[9] Rausche, F. (2000), 'Pile driving equipment: Capabilities and properties', Keynote Lecture, *Proceedings of the 6th International Conference on the Application of Stress-Wave Theory to Piles*, Sao Paolo, Brazil.

[10] Hussein, M.H., Rausche, F. and Likins, G.E. (1992), 'Dynamics of pile driving as a function of ram drop height', *Proceedings of the 4th International Conference on the Application of Stress-Wave Theory to Piles*, The Netherlands, 421-424.

[11] Flynn, K.N., McCabe, B.A. and Egan, D. (2013), 'Axial load behaviour of a driven cast-in-situ pile in sand', *Proceedings of the 7th International Conference on Case Histories in Geotechnical Engineering*, Chicago, USA, 1–6.

[12] Flynn, K.N. (2014), *Experimental investigations of driven cast-in-situ piles*, PhD Thesis, National University of Ireland, Galway, Ireland.

[13] http://www.junttan.com/products/hydraulic-impact-hammers/ accessed April 2016.

[14] Flynn, K.N. and McCabe, B.A. (2016), 'Shaft resistance of driven cast-in-situ piles in sand', *Canadian Geotechnical Journal*, Vol 53, Issue 1, 49-59.