HAMMER PERFORMANCE EVALUATIONS

Steve Abe[1] and Gabriel Thendean[2]

Abstract

One of the primary objectives of performing dynamic pile monitoring with a Pile Driving Analyzer is to evaluate hammer performance. The most common measure of hammer performance from dynamic pile monitoring is the energy transfer efficiency (ETR) which is calculated by dividing the time integral of measured force and velocity (the transferred energy) by the rated hammer energy. Typically, the performance of a given pile driving system is evaluated by comparison of it's ETR to the statistical results of a similar hammer-pile systems compiled from numerous projects. The ETR is governed by the hammer efficiency and other parameters of the driving systems, as well as the hammer-pile combinations. Therefore, ETR is a measure of the pile driving system performance and not just the hammer.

Parametric studies using wave equation analysis were performed to evaluate the effects of individual pile driving system parameters on hammer performance for the general categories of pile driving systems. The parameters are hammer and pile cushion stiffness, pile impedance, percent shaft resistance, capacity or driving resistance, and cap to ram weight ratio. The results provide a general insight as to what extent hammer performance can vary within a given category due to other factors besides the commonly blamed hammer efficiency. The results also help, when reviewing ETR from dynamic pile monitoring, in explaining whether hammer performance that appears to be above or below the statistical mean should be attributed to a hammer problem or to other parameters of the pile driving system. For both air and diesel hammers on concrete and steel piles, the variation range are superimposed on the ETR histograms.

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[1] Senior Engineer, GRL & Associates, Inc., 3667 Northridge Drive, Concord, CA 94518
[2] Senior Engineer, GRL & Associates, Inc., 4535 Emery Industrial Pkwy, Cleveland, OH 44128

Background

To understand the terminology used in this paper the following definitions are important. The rated energy is a value selected by the manufacturer as a theoretically achievable energy in the hammer prior to any losses such as friction during the descent of the ram. The ram impact energy is available in the instant preceding impact. The ram impact energy is usually lower than the rated energy because of losses such as a stroke less than maximum, friction, or an inaccurate timing of motive fluid injection (preadmission, preignition). The energy transferred to the pile is even lower because of losses occurring during impact, in particular, due to cushion compression, an impact that is non-axial, plastic pile top deformation or other energy losses occurring between hammer and pile.

A pile driving system is defined as a combination of pile driving hammer, pile, anvils, pile caps, hammer cushions and/or pile cushions that exist between the hammer ram and pile top. Therefore, the performance of a pile driving system is governed not only by the hammer efficiency but also by the individual and combined effects of each of these components.

The performance of a pile driving system (commonly known as hammer performance) is crucial to the resultant quality of the foundation. Excessively low hammer performance can result in low bearing capacity, insufficient pile penetration, and reduced pile driving production. Higher than expected hammer performance can cause high pile stresses and eventually pile damage. Thus, it is very important to perform dynamic pile measurements with a Pile Driving Analyzer (PDA) to evaluate hammer performance before commencing production pile driving. For a large pile driving project, the hammer performance should also be evaluated regularly during production pile driving as part of the project quality control, or when a different driving condition is encountered.

Based on these energy considerations, two classifications of hammer performance exist.

(i) **Hammer Efficiency, E_h,** is the ram impact energy divided by the manufacturer rated hammer energy.

$$E_h = \frac{\frac{1}{2}\, mv^2}{E_r} \tag{1}$$

Where m is the mass of the ram, v is the ram impact velocity (either measured or calculated), E_r is the manufacturer rated energy.

(ii) **Energy Transfer Efficiency, ETR**, is the maximum energy transferred to the pile top (EMX) divided by the manufacturer rated hammer energy.

$$ETR = \frac{EMX}{E_r} \tag{2}$$

EMX is calculated by the PDA from dynamic measurements of force and velocity during pile driving using the following equation.

$$EMX = \max.\ [\ \int FV\ dt\ ] \tag{3}$$

The hammer efficiency, E_h, has the greatest effect on ETR and is the required input for wave equation analysis except when an extremely soft cushion adds particularly large losses. The hammer efficiency is not directly obtained from dynamic pile measurements. However, it can be computed from ram impact velocity (v) measurements made with a radar based Hammer Performance Analyzer (HPA). ETR can also be estimate from wave equation analyses using the GRLWEAP Program by dividing the calculated energy transfer to the pile (ENTHRU) by the rated hammer energy, Er.

Average hammer efficiencies have been back calculated for various hammer types based on back analysis using wave equation analysis, and ETR results obtained from dynamic pile measurements. These efficiencies are recommended for wave equation analysis input by the GRLWEAP manual (GRL, 1995) as follows.

$E_h = 67\%$ for single acting air hammers.
$E_h = 80\%$ for open end diesel hammers with atomized fuel injection.
$E_h = 95\%$ for hydraulic hammers.

Comparison of ETR is the most common method of evaluating hammer performance from dynamic pile measurements. The measured ETR for a specific pile driving system is typically compared to statistical results (also presented as histogram) from many similar pile driving systems compiled from numerous projects. The statistical results and histograms for various pile driving systems are presented in the PDA manual (Pile Dynamics, 1995) and are summarized in Table 1. More cases for hydraulic hammers are needed for better statistical representation.

Table 1: Summary of Statistical Results of ETR Compiled from PDA Results at Numerous Projects (Extracted from PDI, 1995)

Hammer Type	Pile Type	Sample			
		Size	Mean %	Standard Deviation %	Range %
Air	Concrete	104	40.4	12.0	7.5 - 72.5
Air	Steel	225	50.2	11.5	17.5 - 72.5
Hydraulic	Concrete	23	51.2	15.9	25.0 - 85.0
Hydraulic	Steel	25	82.0	15.1	45.0 - 95.0
Diesel	Concrete	213	24.8	6.8	7.5 - 52.5
Diesel	Steel	378	34.3	9.4	12.5 - 62.5

Although, the statistical results and histograms are a valuable guide for general hammer performance evaluation, they do not provide an insight into any deviations from average performance. The effects of individual pile driving system components on hammer performance are not shown. For example, a lower than average ETR from dynamic measurements does not necessarily indicate a low hammer efficiency, but may be caused by other parameters of the pile driving system such as a low pile cushion stiffness.

Parameters of the Pile Driving System Effecting ETR

Besides hammer efficiency, some of the parameters effecting hammer performance are hammer and pile cushion stiffnesses, pile impedance, distribution of shaft resistance along the pile shaft (percentage of shaft to total resistance), driving resistance, and pile cap to ram weight ratio. The objectives of this paper are: first, to demonstrate the individual effect of each of these parameters on ETR for various pile driving systems, second, to evaluate which parameter has the greatest effect on ETR for various pile driving systems and irrespective of pile driving system; and finally to present the ETR variation range for each parameter on the hammer performance histograms. These objectives were accomplished by performing a parametric studies using wave equation analysis.

Wave Equation Analysis Study of Pile Driving Parameters

Wave equation analyses were performed using the GRLWEAP, Version 1.995-1 described by GRL (1995). The analyses were performed for single acting air, hydraulic, and diesel hammers on steel and concrete piles combinations, as listed in Table 1. The effect of these parameters on ETR for the six hammer-pile combinations was investigated by varying in the wave equation data input each parameter over the reasonable maximum to minimum range that would be encountered in the industry. The following parameter values, listed in Table 2, were used in all analyses except when that parameter was investigated. All the parameters presented in bold (Table 2) were investigated in this study.

The effect of pile cushion stiffness variation obviously was analyzed for concrete piles only, while all other parameters were investigated for both steel and concrete piles. The pile impedance variation was achieved by varying the pile cross sectional area. The standard GRLWEAP recommended pile material properties (elastic modulus, specific weight, and coefficient of restitution) and dynamic soil constants (dampings and quakes) were used.

Results of Wave Equation Parameter Studies

For each parameter, the ETR at the refusal driving resistance is plotted over the range of the analyzed parameter. For easy interpretation of the plotted results in Figures 1 to 7, solid lines are used for concrete piles and dashed lines for steel piles. Symbols are used to differentiate hammer type such as: filled square, empty triangle, and empty circle are for air, hydraulic and diesel hammers, respectively. Results are discussed on the following.

Hammer Cushion Stiffness

Figure 1 shows the effect of hammer cushion stiffness for all six hammer-pile systems. For all systems, the results only indicate a significant ETR variation when the stiffness is below 1,000 kN/mm (5,760 kips/inch), which is well below the commonly encountered range of stiffness when modern hammer cushion materials such as conbest, micarta, or nylon are used. All analyses for concrete piles show little variation in ETR with hammer cushion stiffness indicating that the pile cushion stiffness governs ETR variation as expected. The combined stiffness of a stiff hammer cushion and a soft pile cushion will result in a soft combined stiffness regardless of the hammer cushion stiffness.

Table 2: Summary of Wave Equation Analysis Input Value

Hammer Input:	
Rated Energy (all hammers)	100 kN-m (73.75 kip-ft)
Ram Weight	
Air and Hydraulic	100 kN (22.5 kips)
Diesel	29.4 kN (6.6 kips)
Rated Stroke	
Air and Hydraulic	1.0 m (3.28 ft)
Diesel	3.4 m (11.2 ft)
Hammer Cushion Stiffness	10,000 kN/mm (57,640 kips/inch)
Pile Cushion Stiffness	250 kN/mm (1,440 kips/inch)
Pile Cap Weight	10 kN (2.25 kips)
Efficiency (standard from GRLWEAP)	
Air	67%
Hydraulic	95%
Diesel	80%
Pile Input:	
Length	30 m (98 ft)
Cross Sectional Area	
Steel	125 cm^2 (18.75 in^2)
Concrete	1260 cm^2 (189 in^2)
Impedance (EA/c)	
Steel	511 kN-s/m (35.0 kips-s/ft)
Concrete	1,247 kN-s/m (85.4 kips-s/ft)
Shaft Resistance Distribution	Uniform and 50%
Driving Resistance	Refusal

Note: Parameters in bold were varied in this study; others were constant for all analyses.

Pile Cushion Stiffness

The effect of pile cushion stiffness on ETR is depicted in Figure 2. The variation is greatest for all hammers at lower stiffnesses from 100 to 500 kN/mm (576 to 2,880 kips/inch) which is a typical range that a plywood pile cushion may have from the new to the compresses or worn condition. Above 1000 kN/mm (5,760 kips/inch), ETR variation was minimal with increasing pile cushion stiffness.

Pile Impedance

The effect of pile impedance variation to ETR is plotted by solid lines in Figures 3 and 4 for concrete and steel piles, respectively. The relationship between refusal pile capacity and pile impedance is also shown in Figures 3 and 4 by dashed lines. For concrete piles, increasing pile impedance results in significant reduction of ETR for all three hammer types, but refusal pile capacity behaves inversely. For both concrete and steel piles, the mobilized pile capacity increases almost linearly with increasing pile impedance up to approximately 2,500 kN-s/m (171 kips-s/ft). For diesel-concrete system, the mobilized capacity reached maximum at impedance of 4,000 kN-s/m (274 kips-s/ft) and then start decreasing. This behavior could also occurs on the external combustion hammers but at a higher pile impedance than shown on the graph. This reduction was caused by increase of pile area to increase impedance but not the pile/hammer cushion area to maintain stiffness. This resulted in incompatibility in the system. This problem could be solved by also changing cushion area.

For steel piles, the effect of pile impedance on ETR is minimal for the air and hydraulic hammers. The diesel-steel system exhibits a similar ETR reduction with increasing impedance as diesel-concrete system, but less significant.

Percentage of Shaft Resistance

Figure 5 shows the effect of the shaft resistance distribution on ETR. Theoretically, for a fixed stroke hammer such as an air or hydraulic with a constant impact energy, increasing soil resistance near the pile top results in smaller pile top displacement and therefore lower ETR (according to Equation 3). Based on Figure 5, this holds true for the air and hydraulic hammer on concrete piles, but on steel piles the ETR is relatively constant over the full range of shaft resistance.

For diesel hammer, the effect of shaft resistance is significant for steel pile and less significant for concrete pile when the shaft resistance is below 45%. Above 45% shaft resistance, the ETR for both piles increases slightly and gradually due to an increased ram stroke with increasing shaft resistance.

Driving Resistance or Capacity

The effect of driving resistance on ETR is presented in Figure 6. For both air and hydraulic external combustion hammers, the results indicate an initial increase in ETR for low driving resistances less than 20 to 50 blows/m (6 to 15 blows/ft). At very low driving resistance, the pile top displacement is large enough to cause a noticeable increase in effective stroke and, therefore, ETR.

The effective stroke, in this case, is the rated stroke plus the maximum pile top displacement. The maximum ETR occurs at driving resistances of between 24 and 50 blows/m (7 and 15 blows/ft) and then decreases with increasing driving resistance. At higher driving resistance, smaller pile top displacement results in lower ETR as energy is reflected back into the hammer resulting in a higher hammer blow rate.

For the diesel hammer, there is an initial decrease in ETR at low driving resistance followed by a slight increase as the ram stroke increase with higher driving resistance. This increase in ETR is minimal as the increasing stroke is countered by the decreasing pile top displacement.

Cap to Ram Weight Ratio

The effect of pile cap weight to hammer ram weight ratio can be seen in Figure 7. The effect varies greatly for the six different hammer-pile systems analyzed. For both external combustion hammers (air and hydraulic), the lightest cap weight resulted in the maximum ETR. Except for hydraulic-concrete system, the ETR decreased to minimum values at cap/ram weight ratios of between 0.4 and 0.5, and then increased. For hydraulic-concrete system, the minimum occurs at a lower cap/ram weight ratio of about 0.2 and then also increased. For the air-steel system, this parameter had the greatest effect on ETR of the parameters investigated. Thus, when dynamic measurements for air-steel system indicate lower than average ETR, the cap/weight ratio should also be investigated.

For diesel hammers driving both pile types, the effect was opposite for that of external combustion hammers. The ETR for both cases increased with increasing cap/ram weight ratios. However, for diesel-steel system this parameter had the least influence on ETR of the parameters investigated.

Hammer Performance Histogram

The ranges of ETR variation for the various pile driving system parameters are superimposed on the hammer performance histogram for air and diesel hammers on concrete and steel piles and presented in Figures 8 through 11. Hydraulic hammer histograms are not included due to insufficient sample data. The ETR range for each parameter is presented on top of the histogram. An up or down arrow following the parameter indicates how the parameter effects ETR. An up arrow means that increasing the parameter value will result in increasing ETR and vice versa. In some cases, the effect is mixed or negligible.

The following is observed from Figures 8 through 11. By increasing pile and hammer cushion stiffness, ETR will also increase with the magnitude depending on the stiffness value (also see Figures 1 and 2). Decreasing pile impedance will cause the an increasing ETR except for air-steel system where the reverse holds. A lower percentage of shaft resistance will generally result in a higher ETR. The effect of cap/ram weight ratio is inversely related for air and diesel hammers. An increase of ETR can generally be achieved by reducing the weight ratio for air hammer, and increasing the weight ratio for diesel hammer (also see Figure 7).

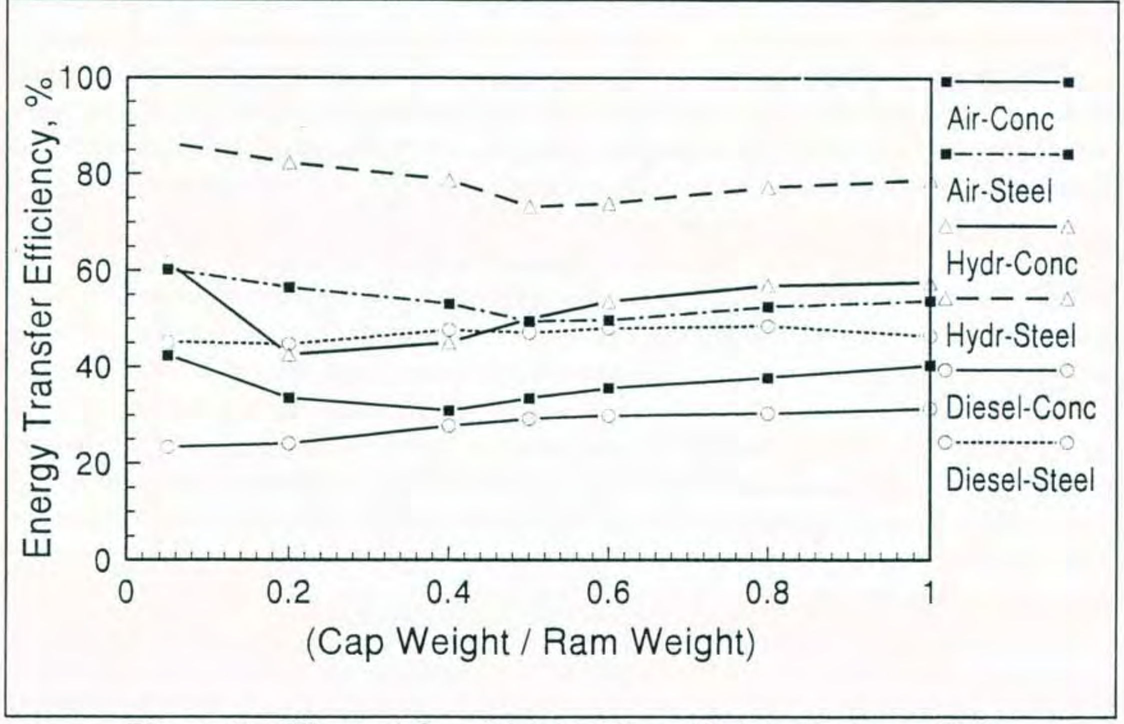

Figure 7: Effect of Cap Weight / Ram Weight Ratio on ETR

For all histogram, except the diesel - steel system, the ETR variation ranges overlapped the mean ETR of the histogram indicating generally a good correlation between wave equation calculated ETR and PDA measured ETR. For the diesel-steel system, however, the wave equation calculated range of ETR were on the high side of the PDA measured ETR histogram, suggesting that the wave equation calculated ETR for diesel-steel system could be too high.

Conclusions

Concrete piles: the wave equation results indicate that for the general pile driving systems analyzed, the greatest ETR variation for concrete piles is effected by pile impedance followed by pile cushion stiffness. All other parameters result in ETR variation less than 20% for all hammer types.

Steel Piles: overall ETR varies much less for the steel pile than the concrete pile regardless of the parameter. The parameter which causes in the greatest variation on ETR is pile impedance for the diesel hammer. Driving resistance and hammer cushion stiffness had the greatest effect for the hydraulic hammer, while cap/ram weight ratio followed by hammer cushion stiffness most effected ETR for the air hammer.

It is suggested that the results presented in Figures 8 through 11 be considered when evaluating hammer performance based on ETR from dynamic pile monitoring results. These figures may be beneficial in explaining variable hammer performance for a given project. It is not implied, however, that these trends will occur for all hammer-pile systems as only one rated energy and two pile sizes were investigated. Furthermore, the combined effects of various parameters were not evaluated. The results are, therefore, intended to provide only general relationships for the parameters discussed rather than represent every possible pile driving system.

References

GRL and Associates, Inc., (1995). "GRLWEAP Manual". 4535 Emery Industrial Parkway, Cleveland, OH 44128.

Pile Dynamics, Inc., or PDI (1995). "Pile Driving Analyzer® Manual". 4535 Emery Industrial Parkway, Cleveland, OH 44128.

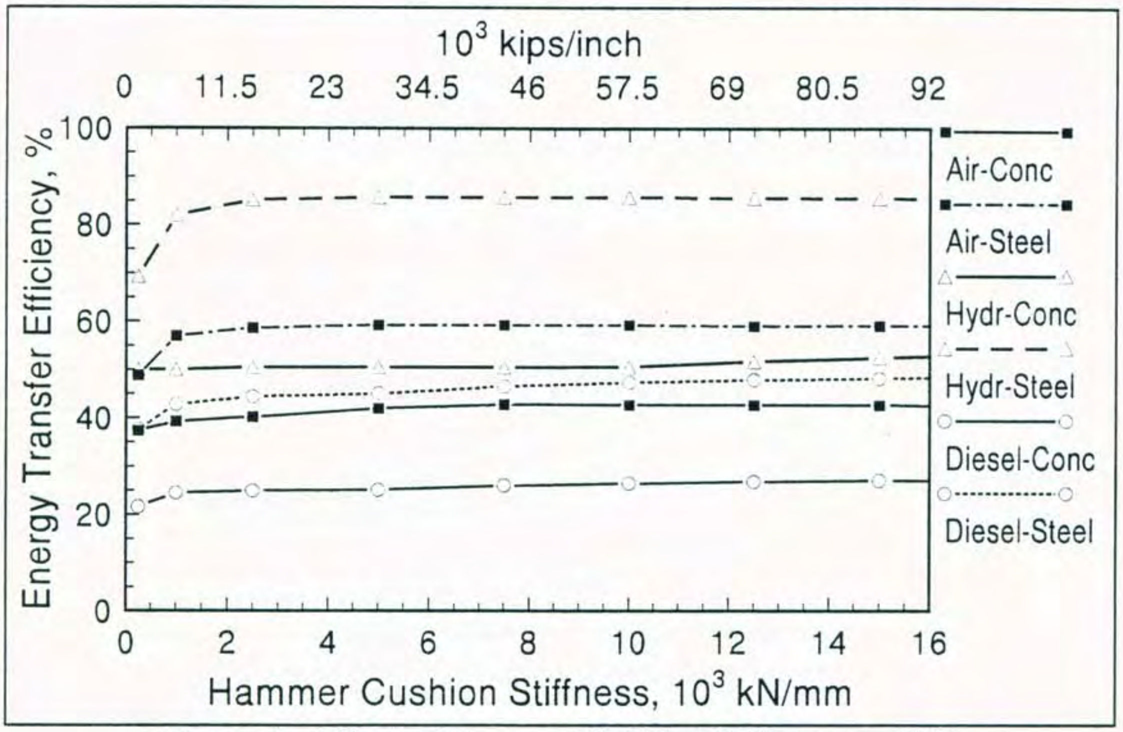

Figure 1: Effect of Hammer Cushion Stiffness on ETR

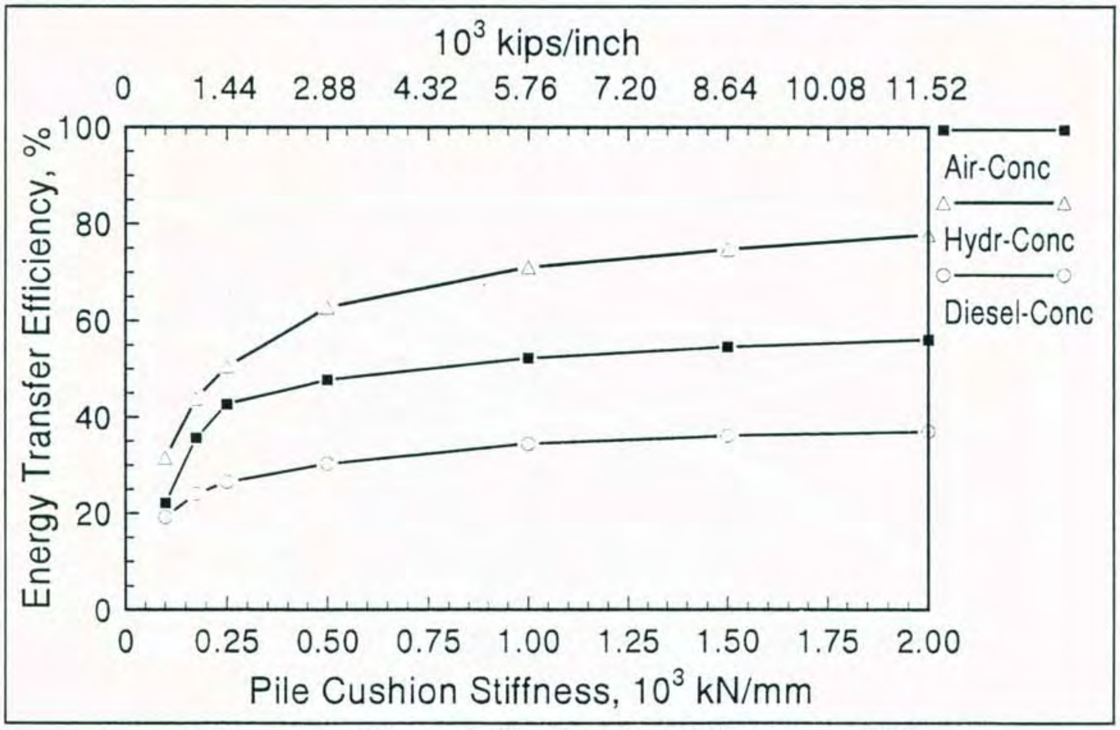

Figure 2: Effect of Pile Cushion Stiffness on ETR

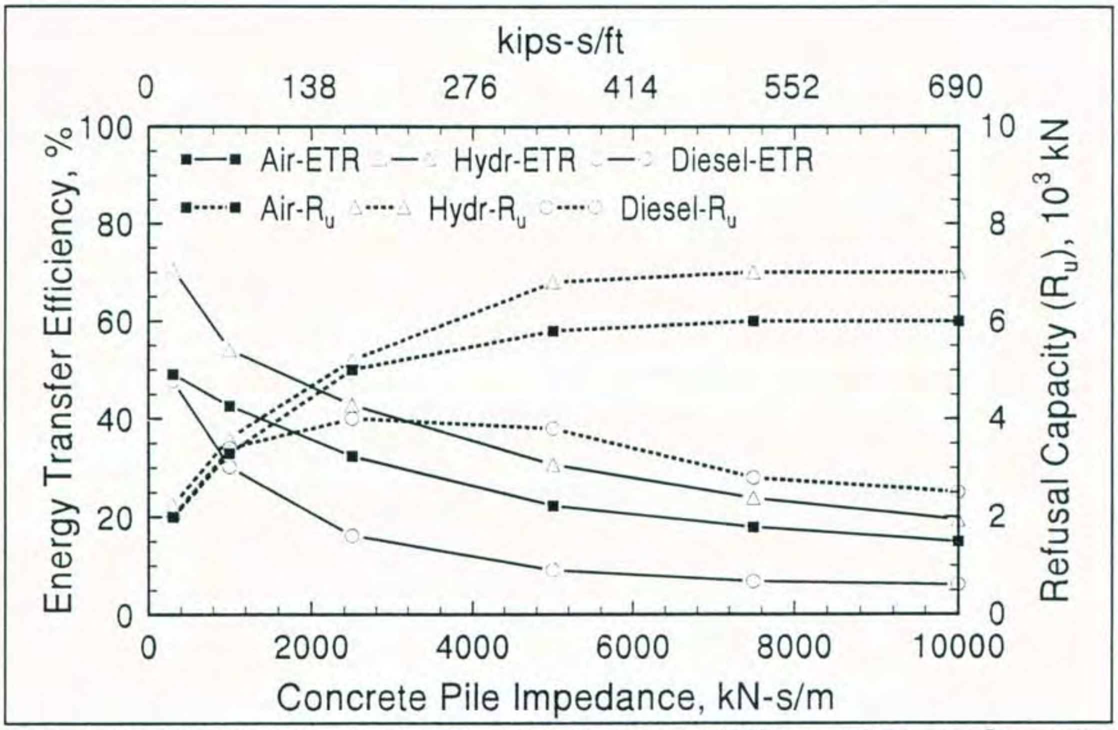

Figure 3: Effect of Concrete Pile Impedance on ETR and Refusal Capacity

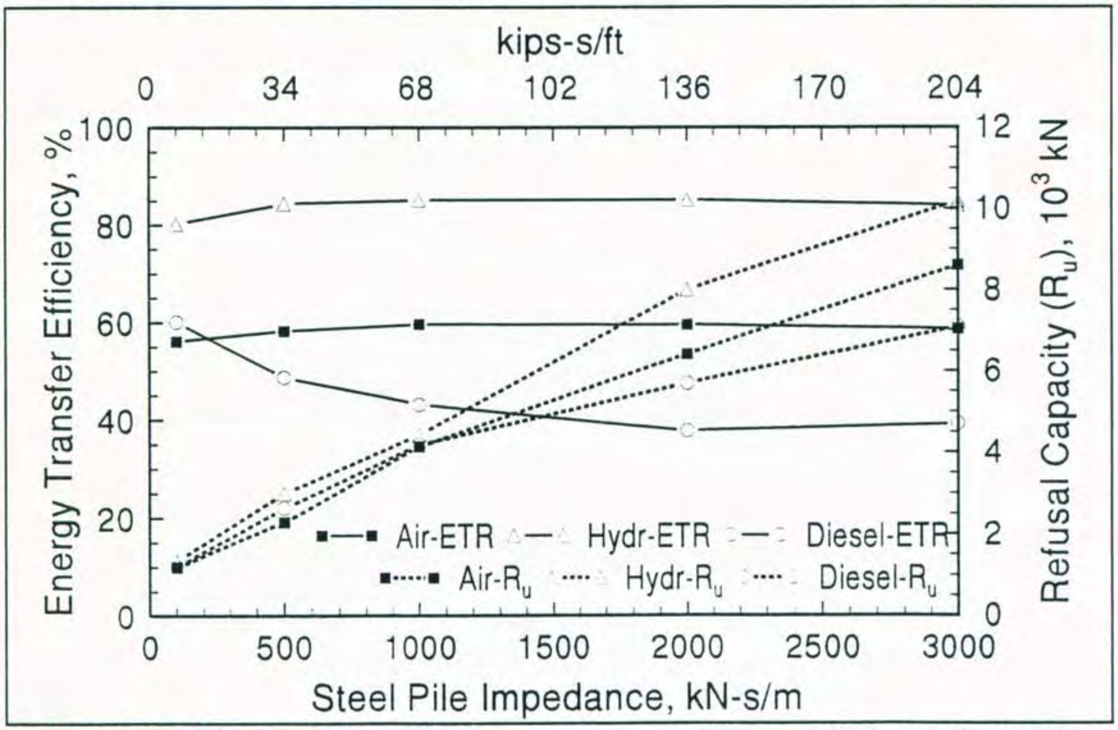

Figure 4: Effect of Steel Pile Impedance on ETR and Refusal Capacity

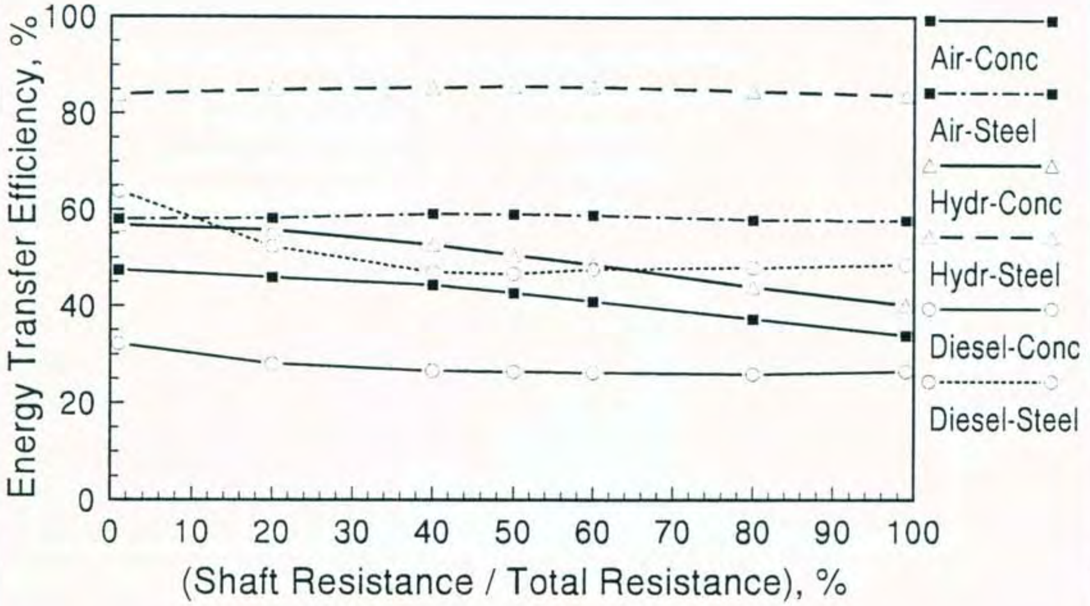

Figure 5: Effect of Percent Shaft Resistance on ETR

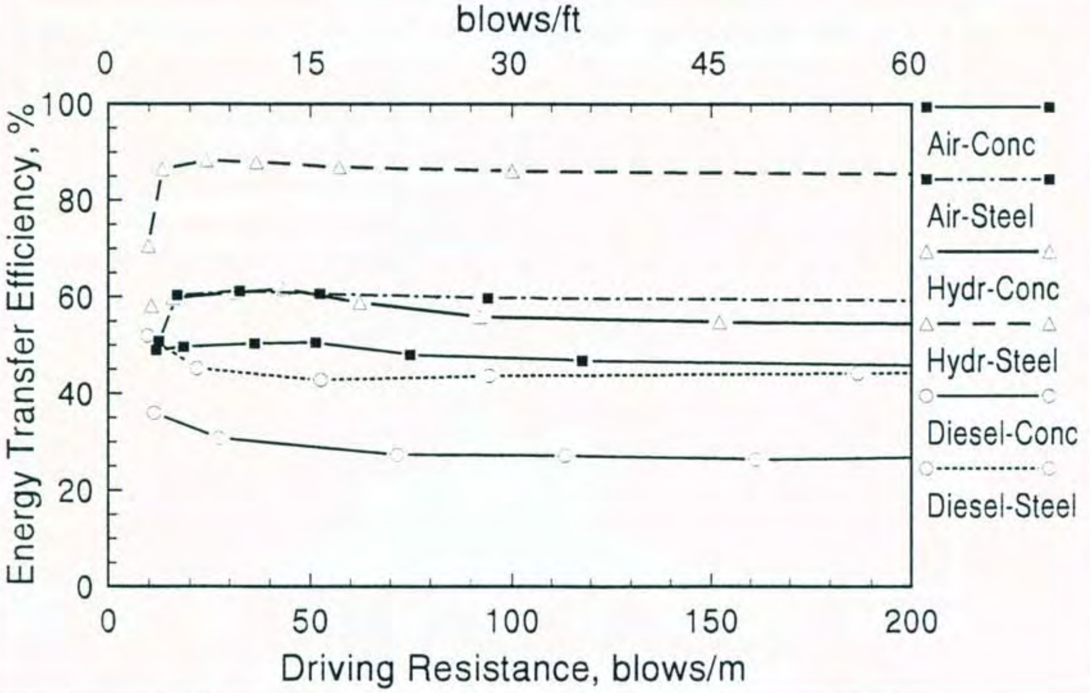

Figure 6: Effect of Driving Resistance on ETR

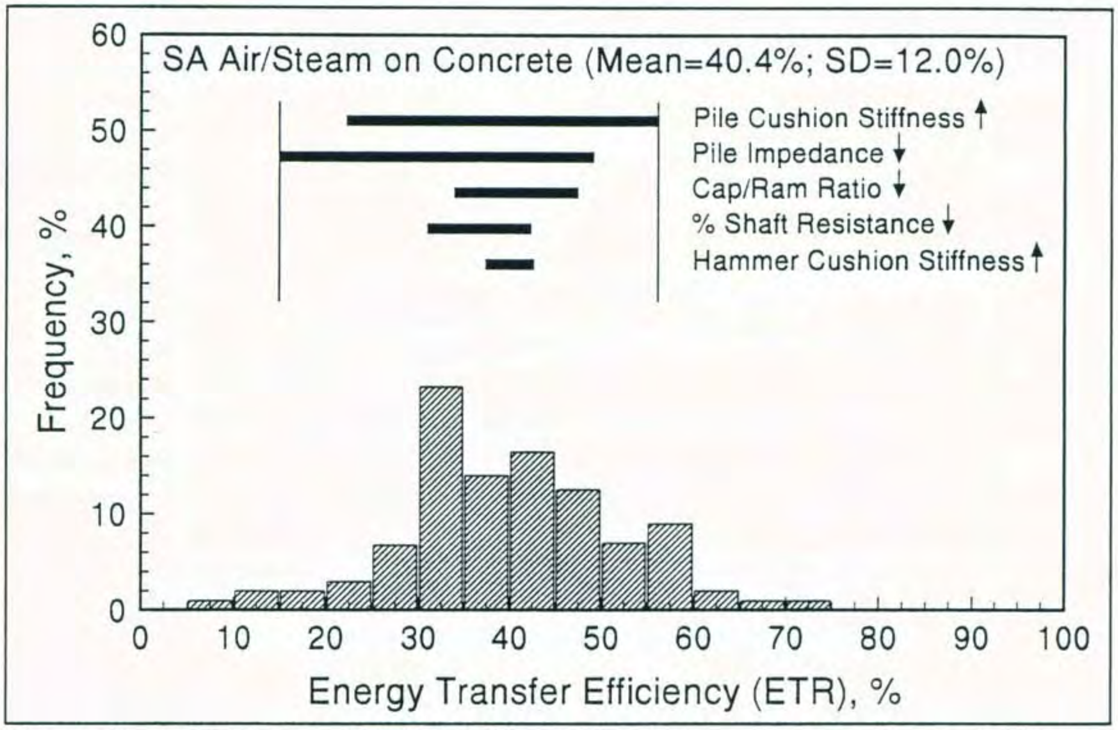

Figure 8: Histogram of ETR for SA Air/Steam Hammer on Concrete/Timber Piles

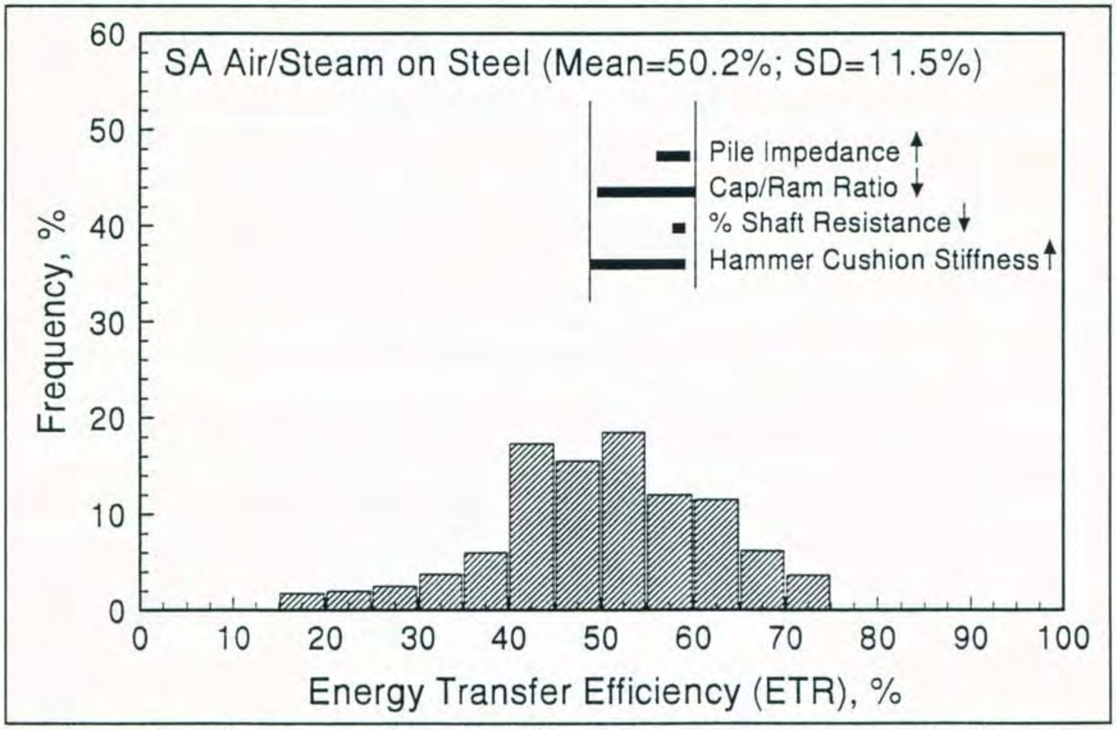

Figure 9: Histogram of ETR for SA Air/Steam Hammer on Steel Piles

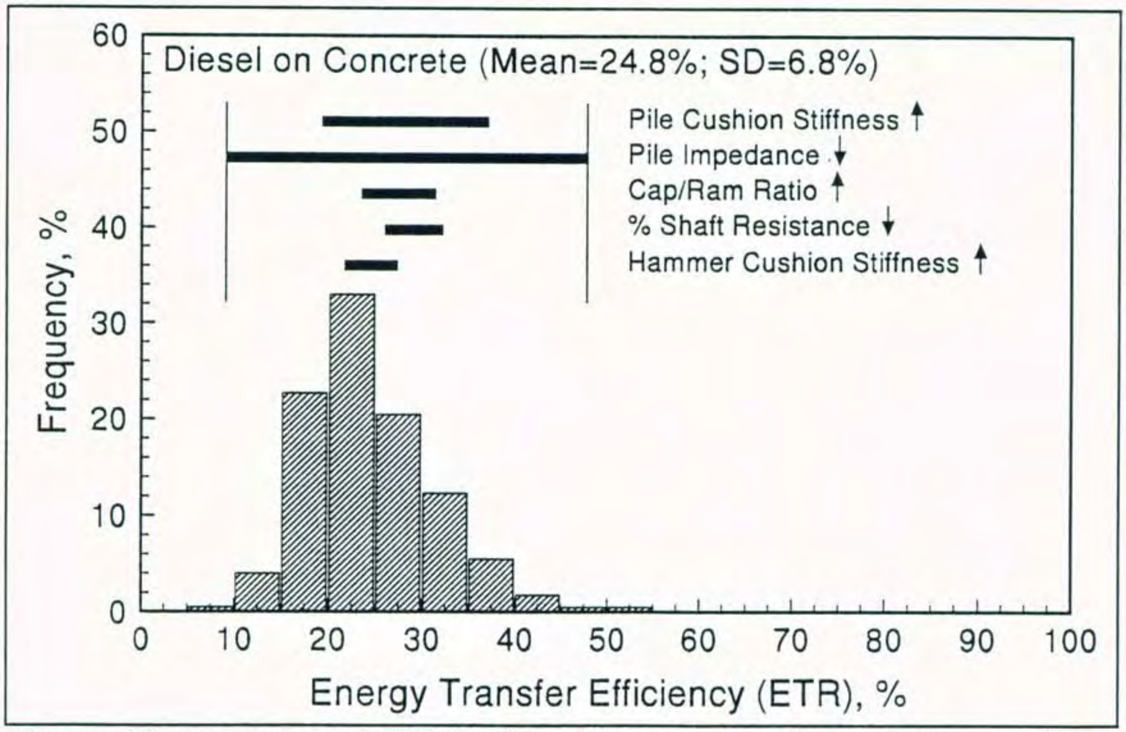

Figure 10: Histogram of ETR for Diesel Hammer on Concrete/Timber Piles

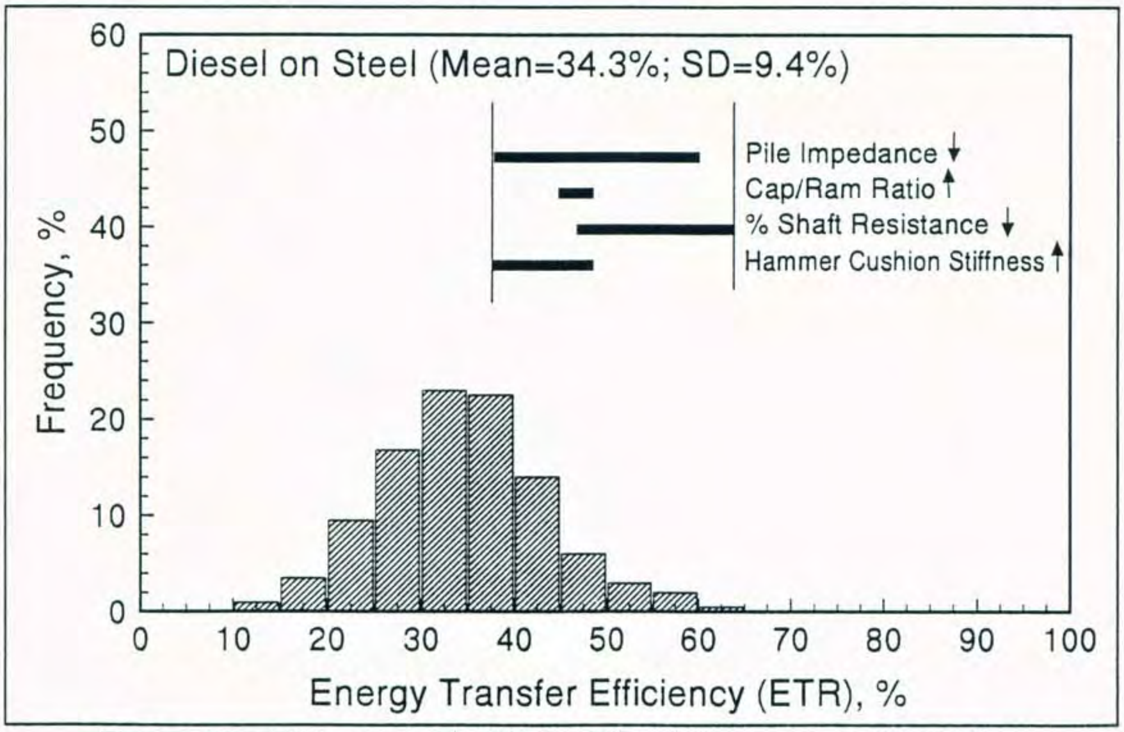

Figure 11: Histogram of ETR for Diesel Hammer on Steel Piles