Intelligent Pile-Driving with a Diesel Impact Hammer

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This paper describes the technology behind the development of an automated energy control system for a diesel pile hammer. Some background is given on experience using an energy monitoring system on the Route 1/I-95 interchange in Alexandria, Virginia. An adjustable hammer throttle and feedback from an energy monitoring system was then used to create a fully automated hammer energy control system. The performance of this system is described in reference to a piling project in Canada where the automated energy control system was used to obtain an unprecedented level of quality control and assurance – data and graphs from the project are presented. The hammer energy control system (ECS) was used to successfully control and maintain a prescribed impact energy for the diesel hammer. This paper presents the first ever results from a truly automated diesel pile hammer and points to a new direction in quality control and assurance in pile driving.

INTRODUCTION

History and Background

Diesel Pile Driving Hammers were first produced by Delmag in 1938 in Germany[1]. The technology was first used in North America in 1953 by Bermingham Construction Limited of Ontario, Canada[2] – see Figure 1.

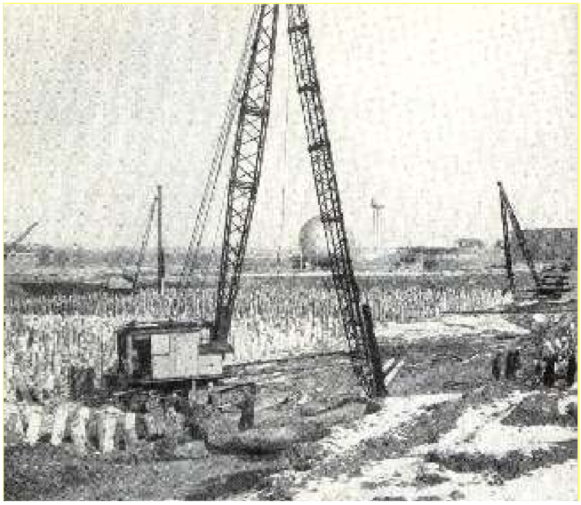

Figure 1 – Three Bermingham Construction rigs driving timber piles with diesel pile hammers in the early 1950's

The technology behind the diesel hammer has not changed significantly since that time and the underlying principle is simple: Diesel fuel is ignited by the compression of air beneath a falling mass. This combustion event, together with the elastic collision between the falling mass and the pile (and other intermediate bodies), produces the required energy to return the falling mass to a sufficient height such that a self-sustaining, repetitive process is achieved. The purpose of this process is, of course, to drive a pile into the ground. The basic 'cycle' for a diesel hammer is shown in Figure 2.

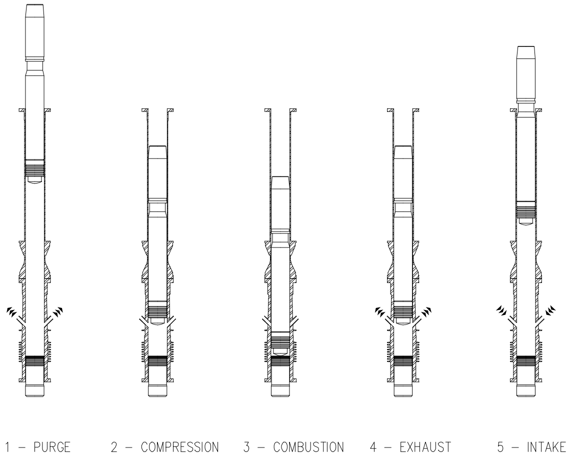

Figure 2 – Combustion Cycle for a diesel pile hammer

The basic principles of the diesel hammer have not changed in the past 65-years, however, in the last 15-years industry demands have created the need for better quality control and quality assurance in pile driving. This paper will explore advances in the area of diesel hammer monitoring, control and automation, highlighting one project where an energy ***monitoring*** system was used and detailing one project where an energy ***control*** system was used.

Controllability of Diesel Hammers

One of the main misconceptions about diesel hammers is that they are not controllable. This is partly due to the fact that unlike hydraulic hammers, diesel hammers are ‘coupled’ to the pile. In other words, the performance (impact energy) of a diesel hammer depends on the soil resistance, and the mass and stiffness of the pile foundation being driven. Likewise, the resulting capacity of the pile foundation depends on the performance of the pile-driving hammer. In contrast, the impact energy or ‘stroke’ of a hydraulic hammer is relatively independent of the pile resistance. The interdependency of the pile capacity and the hammer performance for a diesel hammer can add an extra level of complexity and uncertainty to the pile installation process, and for diesel hammers has created a reputation of ‘uncontrollability’.

Proponents of diesel hammers tend to view the interdependency of the pile resistance and the hammer performance as an advantage rather than a disadvantage. When driving concrete piles the impact energy of a diesel hammer will be low when the soil resistance is low, thus helping to minimize potentially damaging tension stresses.

Another concern with diesel hammers is that the impact energy may suddenly increase and over-stress the pile. This can be a concern when driving piles through very soft soil to a hard rock bearing layer.

Traditional diesel hammers are equipped with discrete ‘energy settings’ (4-settings are common). These settings control the amount of fuel delivered to the hammer, and thus the resulting ‘stroke’ and impact energy. More modern diesel hammers are equipped with an infinitely adjustable fuel delivery or throttle mechanism, which gives the operator better control over the hammer performance, up to the maximum performance ‘permitted’ by the pile resistance. One such throttle mechanism uses a small hydraulic line connected to a hydraulic hand-pump to control the position of a needle valve. The needle valve regulates the flow of fuel to the combustion chamber of the hammer and hence the impact energy. A well-designed hydraulic-and-needle-valve-system produces a direct relation between the impact energy of the hammer and the hydraulic hand-pump pressure. Figure 3 shows the relationship between the hydraulic hand-pump pressure and the hammer impact energy. A typical hydraulic hand pump is shown in Figure 4.

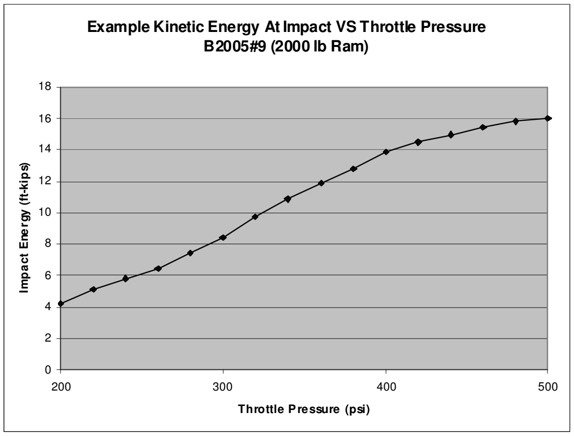

Figure 3 – Graph of infinitely adjustable hydraulic throttle pressure vs. impact energy

Figure 4 – Adjustable hydraulic throttle

These newer developments in throttling have increased the controllability of diesel hammers, but these developments are not well known in the industry; the general impression of diesel hammers is still one of ‘uncontrollability’.

Verifying Hammer Impact Energy

On modern construction sites there is a new emphasis on quality assurance and quality control. In pile driving, ‘QA’ and ‘QC’ typically consist of pile installation records that log the number of blows per unit of penetration, and the final tip elevation for each pile. Very often, however, the performance of the pile hammer is not logged on the pile installation record, or more disturbing, the pile hammer may appear to be operating at the desired impact energy, while in fact it is not. This can lead to a potentially dangerous situation, whereby piles are believed to have more capacity than they actually do.

Historically, the most common problem with diesel hammers has been the phenomenon of 'pre-combustion' or 'pre-ignition'. This problem still exists for diesel hammers that operate using a fuel delivery system known as impact-atomization. In this system, diesel fuel is introduced beneath the falling ram in a liquid state. The liquid fuel spends a split-second in contact with the bottom of the combustion chamber known as the impact block (or anvil). The impact of the ram then disperses the fuel and atomizes it sufficiently for combustion to occur. Pre-ignition occurs when the surface of the impact block becomes very hot (after continued hammer operation) and combustion begins prior to the impact of the ram. Unfortunately, a diesel hammer that is experiencing pre-combustion may not show any visible signs of a problem. The combustion pressure may still be sufficient to 'run' the hammer with the desired stroke, yet the impact velocity may be reduced because of the increased gas pressure beneath the falling ram prior to impact.

Most modern diesel hammers that operate using a fuel injection system do not experience pre-ignition. This can be verified using an instrumentation port that allows for monitoring the impact velocity of the ram using magnetic proximity switches – see Figure 5. Testing has shown that fuel injected hammers do not experience a loss in impact velocity as the hammer temperature increases. This innovation has lead to further development of the velocity monitoring system to include other features for greater QA and QC in pile driving. In 1990, a device was introduced called a Pile Driving Monitor (PDM) that included a depth logger and blow counter, calculated impact energy, pile number, cut-off elevation, date, time, project name, splice location, and various other pertinent information. The unit also had a small printer for a hard-copy of the electronic pile driving log – see Figure 6. Updated versions of the PDM are seeing increased usage in the US market, although the printer has been replaced by internal flash-memory, downloadable to a computer – see Figure 7.

Figure 5 – Magnetic proximity switches installed in the upper-cylinder of a modern diesel hammer

Figure 6 – Pile Driving Monitor from 1990

Figure 7 – Pile Driving Monitor from 2002

During the 1980's and 90's, companies in America and The Netherlands were also developing and popularizing the use of high strain dynamic testing of piles, commonly known as PDA (Pile Driving Analysis or Pile Dynamic Analysis). Using PDA, engineers can affix strain and acceleration transducers to the pile and monitor the pile stress, delivered energy, and using computer models they can predict pile capacity. This innovation has proved extremely useful in assessing the suitability of a pile hammer for a particular job. This assessment is best done during a test-pile program. Many State DOT's use PDA testing routinely in their assessment of a particular pile and pile hammer combination.

Another innovation used to improve the QA and QC for pile driving was an acoustic blow-counter. This device uses sound to detect the blow-rate of a particular hammer, and using a basic formula, the device can estimate the stroke, or the potential energy of a hammer. It also offers the ability to do blow counts, and to store other pertinent QA and QC information. While the original versions of this device offered no ability to detect impact velocity, there is a newer version of the device that uses proximity switches, very similar to the PDM, that allows it to monitor impact velocity. This system requires clear access to the falling ram, which is not always possible in a diesel hammer or a hydraulic hammer unless special provisions are made by the hammer manufacturer.

'Efficiency' and the Need for Impact Energy Monitoring

Since the introduction of PDA testing, the concept of 'energy efficiency' has become popular when discussing pile driving equipment. The efficiency (as it is discussed in the 'popular' sense) can be defined as the percentage of a hammer's rated energy that gets delivered to a pile (as measured by a PDA testing system).

It is the nature of diesel hammers that some portion of the hammer's potential energy (ram mass x actual stroke) is used to compress air used for combustion. This results in an impact energy (or kinetic energy) that is less than that of a theoretically perfect falling mass – see Figure 8. Hydraulic hammers, in contrast, operate using a remote power source (power pack), and do not need to use any of the ram's potential energy for the operation of the hammer, although frictional and other losses still occur. Unfortunately, the industry 'rates' hammers using the maximum 'potential energy' of the hammer, which is clearly a flawed rating system when comparing diesel and hydraulic hammers. When using this flawed system of defining 'efficiency', diesel hammers are at a distinct disadvantage.

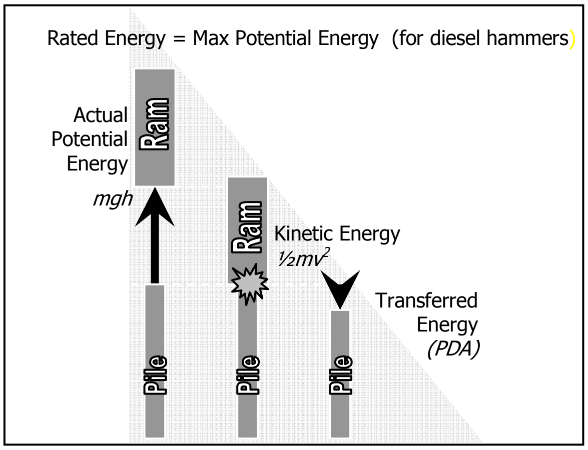

Figure 8 – Description of Potential, Kinetic, and Transferred Energy

More recently, the industry has begun correcting its terminology. What might have been referred to as 'efficiency' only a few years ago, is now referred to more correctly as the 'energy transfer ratio'. This ratio is of interest when performing drivability studies, but should never be used to assess the 'efficiency' of a particular hammer. Improper use of the word efficency has actually caused diesel hammers to be **excluded** from project specifications. One such specification actually declared that; "Diesel hammers will not be allowed due to their *inefficiency.*" These types of comments are cause for great concern, and illustrate the importance of proper use of language in engineering. The mis-use of the word efficiency has undoubtedly hurt the market for diesel pile hammers, and there is a large segment of the foundation industry that still have the false impression that diesel hammers are inefficient. (*The true energy efficiency of a pile-driving system needs to consider the amount of 'work' performed in a given period of time, and the amount of diesel fuel consumed to perform that work).*

The 'nature' of the energy delivered by a diesel hammer and a hydraulic hammer is fundamentally different. A diesel hammer uses a small mass at a high impact velocity to produce impact energy, while the converse is true of a hydraulic hammer – see Figure 9.

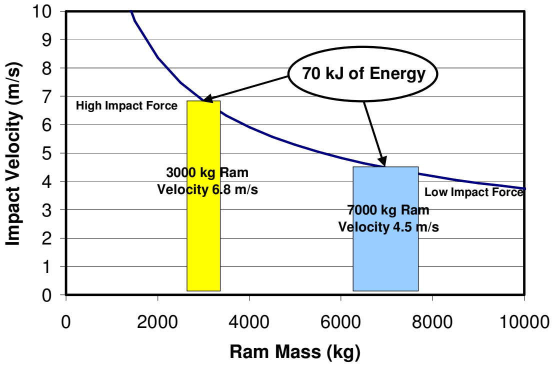

Figure 9 – Relationship between Impact Velocity, Ram Mass, and Impact Force

The higher impact velocity of a diesel hammer is commonly believed to be more suitable for steel piles, driven to a high capacity, while the lower impact velocity of the hydraulic hammer is traditionally deemed more suitable for concrete piles. These different characteristics of the two hammer types make them more 'effective' for different types of jobs, with different types of piles and different types of soils. The complications surrounding the whole hammer-pile-soil system makes the evaluation of the effectiveness of a particular hammer very difficult without actually driving a test pile. Even when test piles are driven, it is rare that different hammer types are evaluated. The overall 'effectiveness' of a pile driving hammer is probably best measured by the time required to drive a given pile.

ROUTE 1/I-95

Project Specifications

In specifying the pile driving hammer for use near the Virginia side of the Woodrow Wilson Bridge near Washington, D.C., the Virginia DOT specified that the pile-driving hammer shall have energy monitoring and reporting capabilities. For this reason the project specifications explicitly called for the use of a hydraulic pile driving hammer[3]. This project was one of the several contracts for the construction of the highway approaches on the Virginia side of the Woodrow Wilson Bridge.

Figure 10 – B-6505 Hammer driving 24-in concrete piles at the Woodrow Wilson Bridge

After meetings with the Virginia DOT as well as the project consultants, it was decided that a diesel hammer would be allowed, provided that the hammer was equipped with an impact energy monitoring system, such as the one shown in Figure 7. Figure 10 shows the hammer driving piles.

The piles for this project were 24-in square pre-stressed concrete piles. The piles ranged in length from 50-80-ft. The soil conditions consisted mainly of sand and silt layers on top of a stiff clay. The contractor for this section of the approach bridges was Dawson Bridge Company from Lexington, Kentucky. The hammer was a Berminghammer B-6505 with 202,000-ft-lb of rated energy and a 17,600-lb ram. PDA testing was performed by Aver Technologies, Inc. of Virginia.

Results

The following graphs summarize the results of the driving of the first production test-pile using a diesel hammer with an impact energy monitoring system.

Figure 11 shows the average impact energy per foot of pile penetration. For reference Figure 12 shows the blow count for the pile vs. penetration. Notice that as the soil resistance increases between 32-ft and 42-ft of penetration, the hammer impact energy also increases. This increase was not due to an increase in the throttle of the hammer, but rather an increase in the hammer stroke due to an increase in the soil resistance. When the blow count decreases from 40 to 45-ft of penetration the hammer impact energy increases due to an increase in the throttle setting of the hammer. This data shows the effect that both the driving resistance and the throttle setting can have on the resulting impact energy (stroke) of the hammer.

To truly verify the accuracy of the hammer energy monitor, the data from the monitor was downloaded to a computer and then combined on a common scale with the PDA data from the pile. Figure 13 shows the theoretical 'potential energy' of the ram (stroke x acceleration of gravity x ram mass). The stroke data is calculated by the PDA system using an empirical formula used to relate blows-per-minute to stroke for a typical diesel hammer. Notice that the stroke vs. the impact energy is a near-linear relation.

Figure 13 also shows the impact energy as measured by the on-board energy monitor (PDM). Notice that about 40-kip-ft of energy is used to compress the gas for combustion. This energy value is calculated used the formula $E = \frac{1}{2} mv^2$, where m is the ram mass and v is the impact velocity measured by the proximity switches shown in Figure 5.

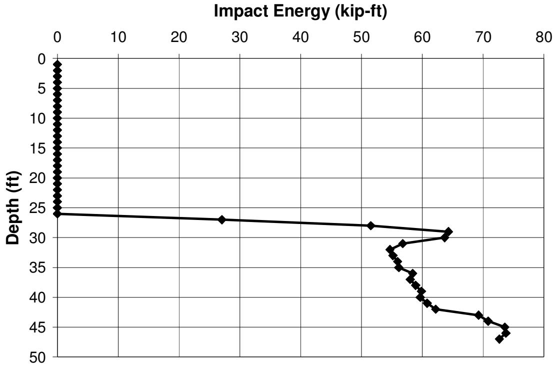

Figure 11 – Average Impact Energy per foot of pile penetration

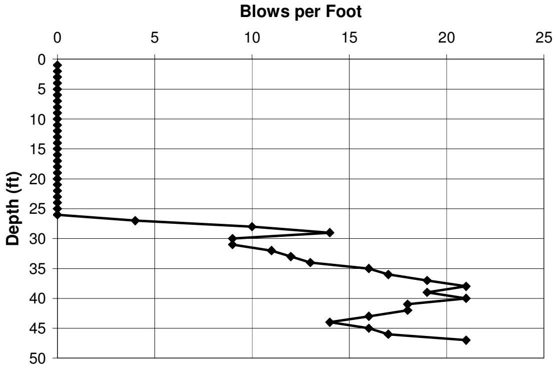

Figure 12 – Pile blow count

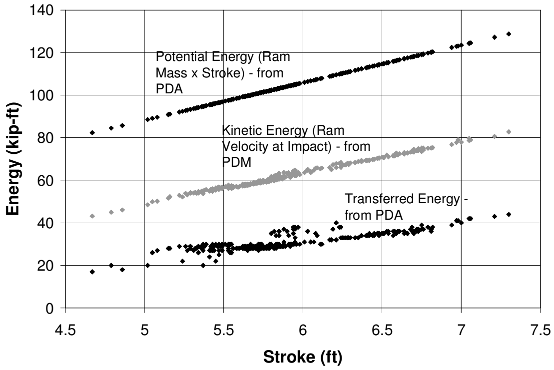

Figure 13 – PDM and PDA Energy Data 'Merged' by hammer stroke

Finally, Figure 13 shows the transferred energy to the pile as calculated by the PDA system. Notice that this data series shows more 'scatter' than the PDM measured impact energy since it is affected by more variables such as pile/hammer alignment, cushion wear, small changes in driving resistance, etc.

Figure 14 shows the same energy data graphed vs. hammer blow number. Note how closely the 2 data-sets follow each other; trending up and down together. This indicates that the PDM is giving results consistent with the PDA data.

Figure 15 shows the relationship between the hammer impact energy and both the compressive and tensile stress in the pile. The compressive stress is clearly related to the stroke of the hammer and as such, setting a maximum allowable stress for a project such as this becomes relatively straight-forward. The tension stress, however, does not show a clear relation to the hammer stroke. This was an expected result since the tension stress is more affected by the pile-toe resistance than the hammer stroke.

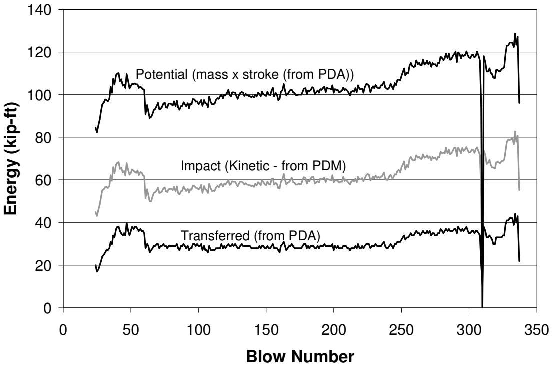

Figure 14 –PDM and PDA Energy Data vs Blow Number on a common scale

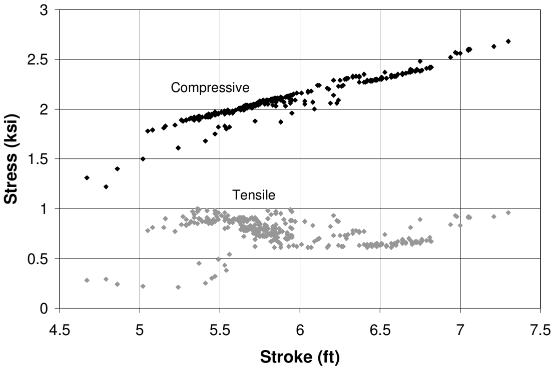

Figure 15 –PDA Stress Data for Tension and Compression vs Hammer Stroke

In general, the energy monitoring system (PDM) used at the Woodrow Wilson Bridge was used as a quality assurance tool for the performance of the hammer. This energy monitoring system was used to verify that consistent energy was used to achieve the required blow counts. Combining the PDM data with the PDA data is instructive since the potential, kinetic (impact), and transferred energies can be studied.

THE ENERGY CONTROL SYSTEM (ECS)

The next logical step in the advancement of technology for diesel hammers was the invention of a hammer energy control system. By combining the functions of the PDM (Figure 7) and the remote hydraulic throttle (Figure 4) and adding basic control-system programming, the first ever diesel hammer energy control system was created (ECS) – see Figure 16.

Figure 16 – Prototype Energy Control System

The ECS contains a small hydraulic accumulator that provides a source of hydraulic flow to operate the throttle. The accumulator is 'pumped-up' at the beginning of the day, and stores enough oil to operate the system for several hours, depending on the amount of 'throttling' the system performs. The control box houses the programming and provides the control for two electronically activated valves that either let more oil into the throttle line (for more hammer energy), or release oil to a tank (to decrease the hammer energy).

Using the ECS requires no modifications to the diesel hammer and requires no additional control lines going to the hammer. The ECS simply makes use of the existing hydraulic throttle line in combination with the cable carrying the data from the proximity switches.

The control box operates on either 120-V AC, or 12-V battery power. The ECS allows the user to set an allowable maximum impact energy – this could be determined by a test pile with PDA testing, or determined theoretically. The ECS also allows the user to select a target impact energy for the hammer to operate at and automatically tries to achieve that energy regardless of the driving resistance (of course the preset energy is not always attainable, especially near the beginning of driving or at other times when the driving is 'soft'.

The ECS used on the following project represents the first attempt (known to this author) to automate the operation of a diesel pile driving hammer.

BUNGE EDIBLE OIL PRODUCTS FACILITY

Project Overview

The Bunge Facility is located in Hamilton, Ontario, Canada on the south shore of Lake Ontario. The pile driving undertaken at this project was performed by Bermingham Construction Limited, also of Hamilton. The project consisted of a three pile types; 100-ton design load 10.75-in pipe with 0.365-in wall thickness, 150-ton design load 11.875-in pipe with 0.582-in wall, and 190-ton design load 13.625-in pipe with 0.625-in wall. All piles were driven closed-end. A total of 268 piles were driven on this site. The project was performed during the months of June and July, 2006.

Soil conditions on the site varied due to the presence of a variety of fill materials. SPT blow counts in the upper layers ranged from 2-30. The underlying native material consisted primarily of silt over stiff clay-till. A weathered shale bedrock was present at a depth of approximately 100-ft. All of the piles were anticipated to be driven to either the stiff clay-till or the shale. Driving was performed using a Berminghammer B-32 Diesel Impact Hammer, with a rated (maximum potential energy) of 81,000-ft-lbs. PDA testing was planned for 10% of the piles. Driving was facilitated by a 70-ton crane equipped with fixed-leads.

Results from the ECS

Approximately one-quarter of the piles on the project were driven using the ECS. This was fewer than planned due to other demands on the time of the primary experimenters. Of this number, the first 17 piles were used to refine the programming of the ECS control logic based on the site and hammer. This process was necessary since this was the first time using the ECS in a project setting. Once the performance of the ECS was deemed satisfactory, 19 piles were driven with the ECS in complete control of the hammer. Of these 19 records, 9 records have been chosen for discussion. It should be noted that the piles were driven in 50-ft lengths and spliced with an additional 50-ft length. Only the data from the driving of the final section is shown. All nine piles selected were 11.875-in pipe with 150-ton design load. The termination criteria for these piles was 12-blows/in with a hammer potential energy of 63-kip-ft corresponding to a 9-ft hammer stroke. The ECS target impact velocity was set to 18-ft/s which corresponded to an impact (kinetic) energy of 36-kip-ft.

Figure 17 – Crane, fixed-lead and Diesel Hammer

In each of the nine following graphs the hammer impact velocity (ft/s) is on the left-vertical axis and the hammer throttle pressure (psi) is on the right vertical axis. The target impact velocity (usually 18-ft/s) is shown as a dashed-line, the actual impact velocity is the black line, and the throttle pressure is the grey line. Each of these variables is graphed sequentially using the blow number on the horizontal axis. The number of blows in each record varies from as few as 300 blows to the longest record which contains 1150 blows, the vertical grid-lines indicate spacing of 100 blows.

In Figures 18 to 26, observe how close the actual impact velocity is to the target impact velocity and notice how the throttle pressure adjusts automatically to achieve the desired impact velocity. Also note that the 'maximum' throttle pressure is 450-psi. This pressure was slightly above the throttle pressure at which the needle valve was completely shut-off, giving the maximum amount of fuel to the injectors. This pressure was programmed into the ECS as the pressure above-which no additional impact velocity was possible.

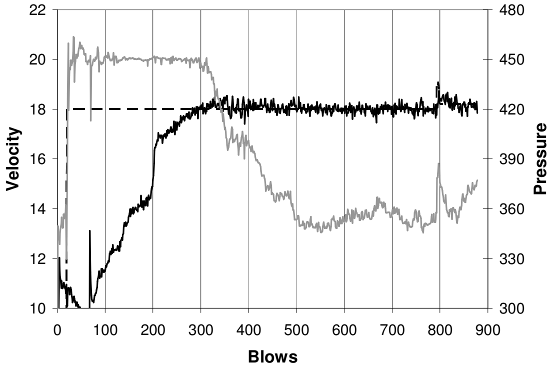

Figure 18 – Record 060606G

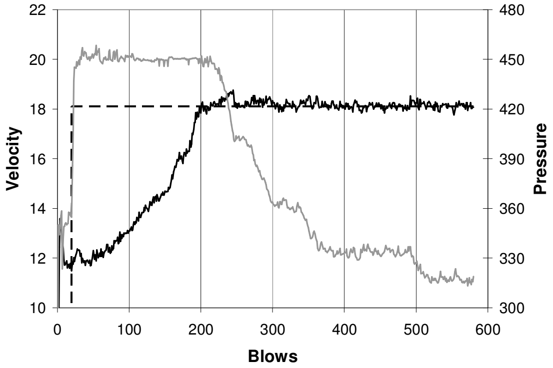

Figure 19 – Record 080606B

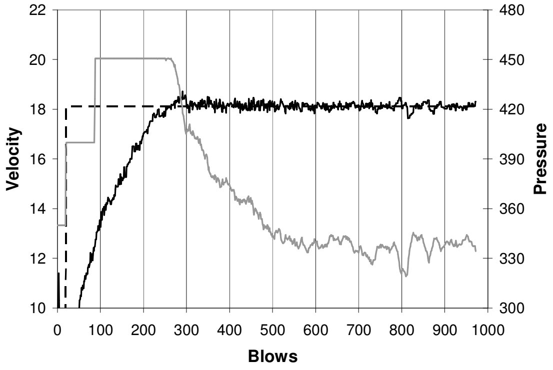

Figure 20 – Record 080606F

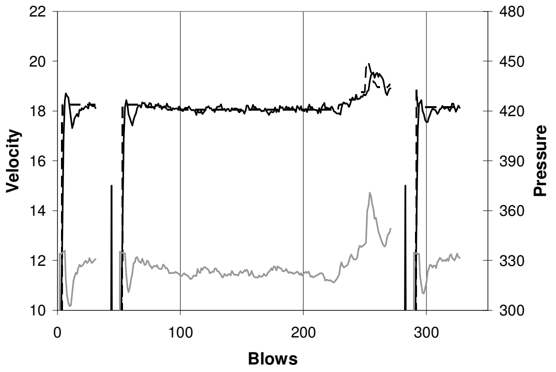

Figure 21 – Record 140606B

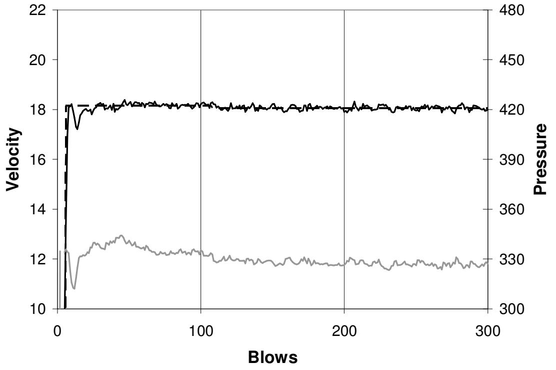

Figure 22 – Record 140606D

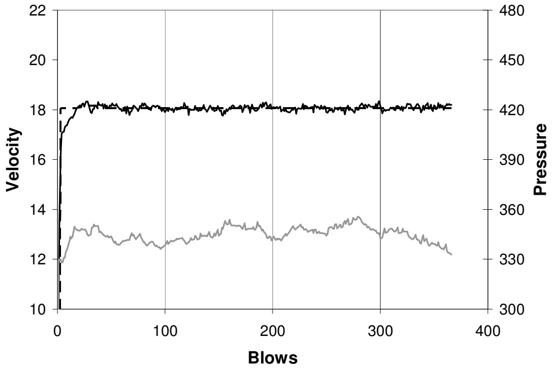

Figure 23 – Record 140606K

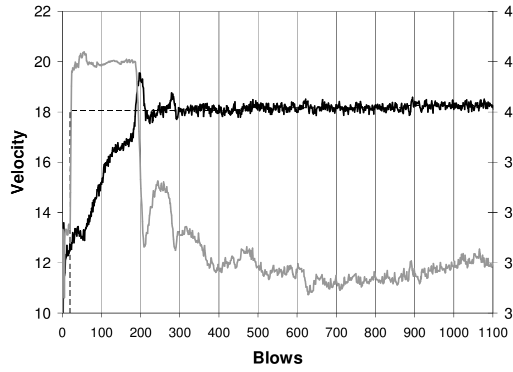

Figure 24 – Record 150606B

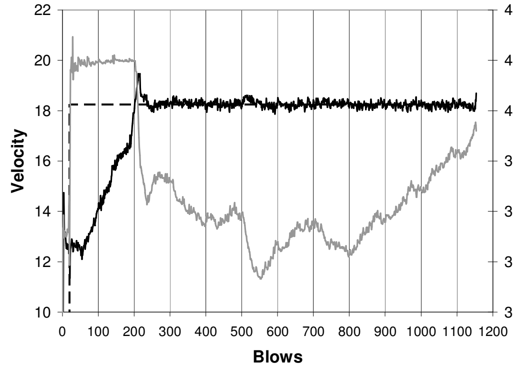

Figure 25 – Record 150606C

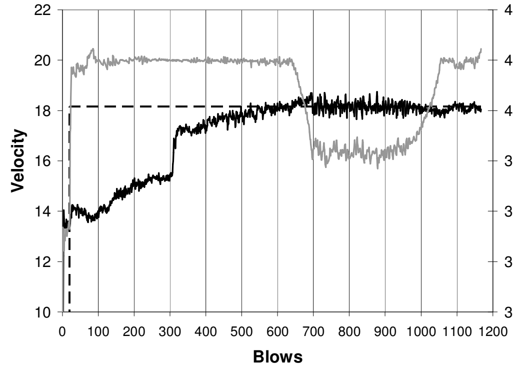

Figure 26 – Record 150606H

In each graph note that the ECS was programmed for a hammer start-up pressure of 300-psi. This was the throttle pressure at which the hammer was known to start. Observe that after 10 blows, the ECS 'engaged' its control logic and attempted to achieve the target impact velocity. This can be seen by the pressure moving up (when necessary) to attempt to increase the impact velocity. Notice in Figure 18, the hammer nearly shuts off after about 50 blows due to very soft driving.

In Figures 18, 20 and 21, the ECS operator adjusted the target velocity to see the response of the ECS and hammer – localized changes in impact velocity are caused by the operator, not the ECS. In Figures 18, 19, and 20 the ECS continuously lowers the hammer throttle pressure to maintain a constant 18-ft/s impact velocity. This occurs as the blow-count increases. On these piles the hammer and ECS could maintain the target impact velocity over the range of blow counts from about 2-blow/in to 12-blows/in. The hammer ran at lower than the target impact velocity for lower blow-counts.

In Figures 22 and 23, the hammer starts driving and is immediately able to achieve the target impact velocity. The ECS makes minor pressure adjustments to maintain the target velocity to the end-of-drive. Variations in the impact velocity are minimal; corresponding to stroke variations of about +/- 3-in.

Figures 24, 25 and 26 are interesting in that they are very long periods of uninterrupted driving – about 1100 blows each, or about 30-min of driving. In Figure 25 there is a slight increase in the throttle pressure starting after about 800 blows. This is thought to be caused by reduced lubrication in the hammer because of the long interval of driving without stopping to grease and oil the hammer. Figure 25 indicates a similar, but more pronounced, phenomenon. Figure 26 is the last record of that day and indicates that the hammer is near full throttle at the end of drive in order to reach the desired impact velocity. It is important to note that throughout this period of hard, continuous driving, the ECS adjusts the throttle to achieve the desired impact energy. It also highlights the importance of stopping to lubricate the hammer at the intervals recommended by the hammer manufacturer. Berminghammer recommends lubricating after every 20-minutes of driving. This particular day was challenging for the hammer, as 8 piles were spliced and ready-to-drive. Time for the hammer to cool was limited to 3-5 minutes between piles.

Figure 21 shows starts and stops in the driving record. These stops were related to affixing PDA gauges to the pile. Figure 27 shows a comparison between the impact energy of the hammer (controlled by the ECS) and the transferred energy to the pile, both measured in kip-ft. Comparing these values gives an energy transfer ratio of approximately 64% using the impact energy at the target 18-ft/s impact velocity (36-kip-ft). Using the potential energy, at a 9-ft stroke (63-kip-ft) the energy transfer ratio is approximately 37%. Both of these values are in the ‘typical’ range for diesel hammers.

Figure 28 shows how well the pile stress can be controlled using the ECS to control the hammer. From blow 50 to blow 200, the target impact energy was left constant (not adjusted by the operator) and the impact force varies between 630 and 660-kips, in direct proportion to the impact force. For this pipe pile (11.875-in diameter, 0.582 wall), these forces translate into stresses ranging from 29.0-ksi to 30.4-ksi; a range of only 1.4-ksi.

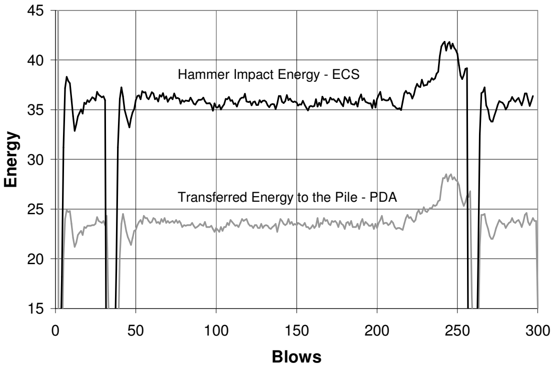

Figure 27 – Impact Energy from ECS and Transferred Energy measured by PDA Testing.

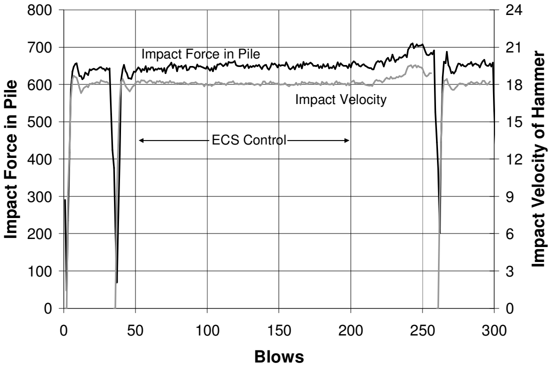

Figure 28 – Impact Velocity of the hammer (ECS) and Impact Force in the Pile (from PDA)

After the initial period of program refinement, the ECS proved that a diesel pile driving hammer can be controlled automatically. In addition to the QA and QC functions already mentioned the ECS is capable of other functions described in the following section. The ECS’s full potential has not been realized, but the 19 piles driven at the Bunge Facility have proven that the concept is not only feasible, but that the energy control is very accurate.

FUTURE WORK

Other experiments planned for the ECS include ‘optimizing’ the speed of the driving, minimizing fuel consumption, and pre-programming the ECS to drive through a given soil profile. It will also be possible to connect the ECS to a PDA device whereby the PDA can inform the ECS if the driving stress is too high and the ECS can reduce the impact force of the hammer accordingly. Additional programming will also be added to inform the operator when the hammer requires service – i.e. greasing and oiling, or when there is an obvious malfunction with the hammer.

SUMMARY AND CONCLUSIONS

This paper has demonstrated the need for energy monitoring and demonstrated its use at the Route1/I-95 project driving 24-in square concrete piles. This paper has also shown a brief history of the development of diesel hammer energy monitoring leading up to the development of the Energy Control System (ECS). This paper has also demonstrated the use of the ECS on a project in Canada. For this project, each pile driven while the hammer was controlled by the ECS, giving an unprecedented level of Quality Assurance.

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