# SPT ENERGY MEASUREMENTS WITH THE PDA

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The Standard Penetration Test (SPT) has long been the most common method of subsurface sampling for geotechnical exploration. The SPT provides a sample as well as information on the properties of the soil in the form of penetration blow counts. However, inconsistencies within the testing procedure itself, such as variations in hammer type and operator variables can have a large effect on the results of the test. The Utah Department of Transportation has conducted a series of SPT hammer energy measurements on a number of hammers using the Pile Driving Analyzer (PDA) to correct the results of the SPT test. The hammer energy was recorded for each blow during the SPT test and the average and standard deviation were calculated for each set of blows. The hammer energies were then corrected to a hammer delivering 60% of the theoretical energy for the system using the average recorded hammer energy. Longitudinal studies of SPT hammer energies indicate that energies can change over time and SPT hammer energies should be checked periodically.

## Introduction

The Utah Department of Transportation (UDOT) has conducted a series of SPT hammer energy measurements on a number of hammers using the Pile Driving Analyzer (PDA). Results from these measurements are then used to normalize the SPT raw blow counts to those of a hammer delivering 60% of the theoretical energy ($N_{60}$). Normalized $N_{60}$ values provide better design parameters when correlated with soil strength, bearing capacity, unit weight, liquefaction susceptibility and other soil properties.

The following paragraphs describe the SPT test and the variations that can occur in the operation of SPT hammers. Details of the PDA instruments recommended for testing SPT hammers and applicable statistics are provided along with a discussion of the characteristics of different types of SPT hammers. The methods UDOT used to test SPT hammer energies, the test results and conclusions are discussed. Recommendations are made regarding the energy testing methods and on going periodic energy testing of SPT hammers.

## The Standard Penetration Test (SPT)

Equipment required for the Standard Penetration Test includes: drive-weight assembly, split-barrel sampler, and drill rods. The drive-weight assembly consists of the hammer and anvil and the hammer drop systems as shown in Figure 1. The ASTM D-1586 (revised 1999) specifications for the SPT test require that a 140 lb. hammer be dropped 30 inches to drive a split tube sampler at the end of a string of drill rods. This process is repeated until the sampler has been driven a total of eighteen inches. In theory, the hammer should deliver 350 ft-lbs of energy (140 lbs x 30 in.) with each blow, however early hammer energy measurements demonstrated that, due to friction and other factors, the energy transferred from the hammer to the sampling rods was actually only 60% of the theoretical 350 ft-lbs or 210 ft-lbs. SPT design theory has been built around the concept of a hammer energy transfer of 60%. Thus each blow count represents a quantum of energy equal to 210 ft-lbs delivered to the sampler. Blow counts could be regarded as a unit measurement of energy where 1 blow count equals 210 ft-lbs.

The blow counts required to move the sampler the last 12 of the 18 inches is a measurement of the standard penetration resistance, N. Empirical formulas for unit weight, shear strength, settlement, liquefaction susceptibility and allowable bearing capacity have been derived utilizing N instead of the direct stress strain relationship which it represents. These formulas are incommonly used and therefore much design work is dependant upon the validity of the N value.

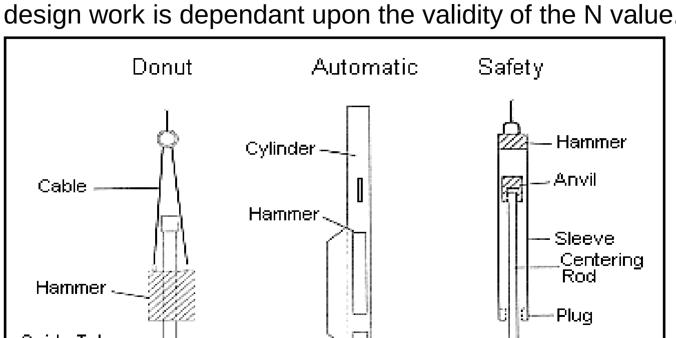


Figure 1, Diagram of SPT Hammers

**Inconsistencies in the SPT**

The theory of the SPT test provides a solid basis for the determination of the engineering behavior of soils, however, many inconsistencies within the test itself introduce a large degree of error making the results unreliable.  According to ASTM D 1586, Section 9.3:

> *Variations in N-values of 100% or more have been observed when using different standard penetration test apparatus and drillers for adjacent borings in the same soil formation.*

Variations in the N-value can most often be traced to a variation in the hammer transfered energy. This is due primarily to a lack of standardization for the hammer and hammer drop system.  The ASTM D-1586 specification permits several varying hammer drop systems: trip, automatic, semi-automatic, and rope and cathead.  In addition, wireline hammer drop systems are also common in practice while not sanctioned under ASTM.  The only requirement placed on the hammer is that it weighs 140 lbs. and has a metal-to-metal contact with the anvil.  Safety, donut, and automatic type hammers are commonly used.  Operator dependant variables can be considerable for all but the fully automatic hammers.  All of these variables lead to inconsistencies in the hammer transfer energy and as a result in the N-values.  An excellent discussion on the SPT procedures is presented Seed et. al., 1985.

**SPT Hammer Energy Testing with the PDA**

UDOT conducted a series of hammer transfer energy measurements using the PDA.  The PDA utilizes two strain gauges and two accelerometers to derive the energy transferred from the hammer to the sampling rods.  Two of each type of gauge were used for averaging and redundancy.  A short segment of NWJ rod was instrumented with the strain gauges and accelerometers as shown in Figure 2.

Two types of accelerometers are available for use with the PDA, piezo-electric and piezo-resistive.  The piezo-electric accelerometers will eventually be destroyed if used in this type of testing because of the high velocities and the resulting high inertial forces on the accelerometers.  Piezo-resistive gauges perform well.

Two methods of measuring energy can be made with the PDA, one method uses only force measurements (Force Squared Method, ASTM D-4633-86) as shown in the following equation:

Where:

$$EF2 = \frac{c}{EA}\int_{a}^{w}\left[F(t)\right]^{2}dt$$

| | |
|---|---|
| EF2 | = the energy delivered to the rod |
| a | = the time energy transfer begins |
| c | = compressional stress wave speed |
| w | = time of zero force after impact |
| A | = cross-sectional area of the rod |
| E | = Young's Modulus |
| F | = force |

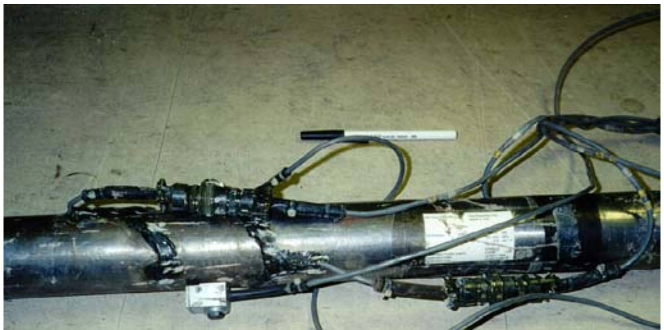


Figure 2. Photo of PDA SPT testing unit.

The other method, which is the preferred method used by UDOT (see ASTM D 6066-96), uses both force and velocity measurements as shown in the equation below:

$$EMX = \int_a^b F(t)V(t)dt$$

Where:

| | |
|---|---|
| EMX | = the energy delivered to the rod |
| a | = the time energy transfer begins |
| b | = the time of maximum energy transfer |
| F | = force |
| V | = velocity |

UDOT tested each rig at three depths ranging from 15 to 50 feet. Twenty-six rigs have been tested to date, 17 automatic, 8 rope and cathead, and 1 wireline (see Table 1). Seven rigs have been tested twice, the majority at approximately 4-year intervals.

Table 1, SPT hammers Tested

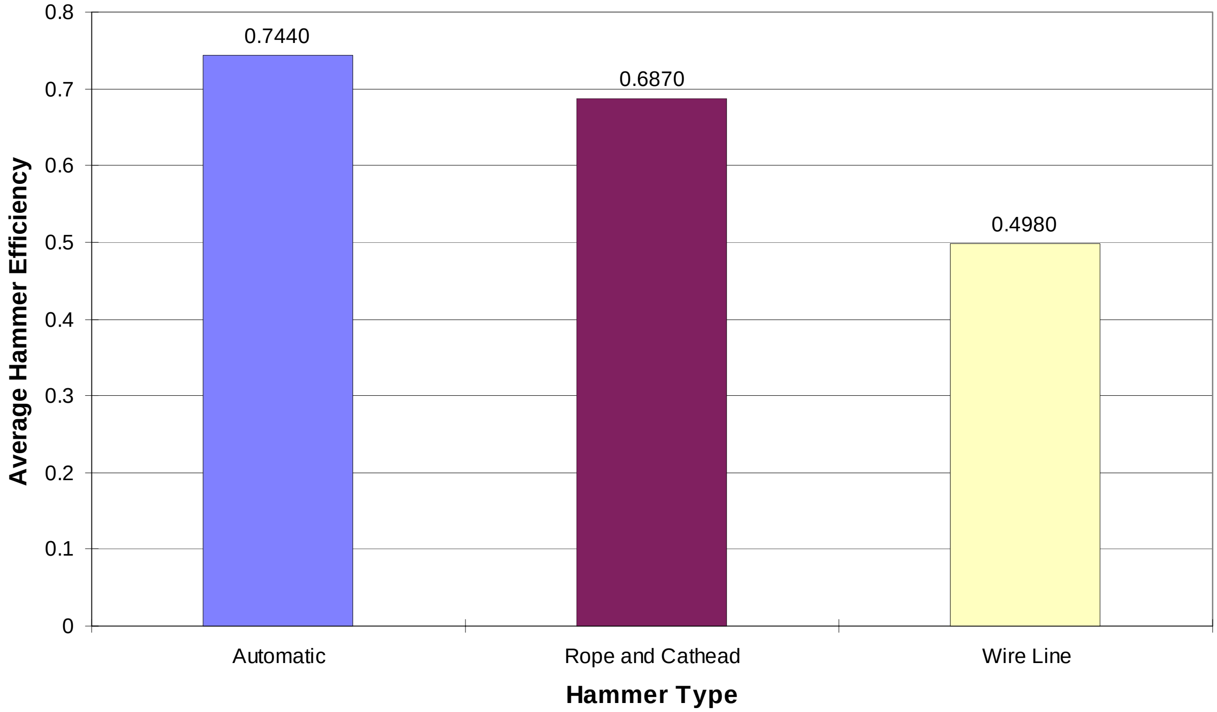
| Automatic | Rope and Cathead | Wireline |
|---|---|---|
| BK-66 | CME 55 | CME 75 |
| BK-81 | Mobile B-53 | |
| CME 55 (2 Rigs) | Mobile B-61 | |
| CME 75 (3 Rigs) | Mobile B-80 | |
| CME 170 | Saitech GH3 (3 Rigs) | |
| CME 750 (2 Rigs) | Terramec 1000 | |
| CME 850 (2 Rigs) | | |
| Diedrich D-120 (2 Rigs) | | |
| Mobile B-53 | | |
| Mobile B-57 | | |
| Mobile B-80 | | |

**Energy Measurement Results**

The tabulated results of all energy measurements are presented in Table 2. Plots of average percent of full theoretical energy for each hammer and combined average efficiency for hammer type is presented in Figure 3. Figure 4 shows similar plots of standard deviations.

Table 2. Energy Measurement Results

| Rig No. | Make and Model | Hammer type | Average Efficiency | Maximum Efficiency | Minimum Efficiency | Std. Dev. |
|---|---|---|---|---|---|---|
| 1 | Mobile B-57 | Rope and Cathead | 0.6220 | 0.8286 | 0.4857 | 0.0460 |
| 2 | Mobile B-53 (1996) | Rope and Cathead | 0.5820 | 0.7430 | 0.3430 | 0.0530 |
| 2 | Mobile B-53 (2000) | Rope and Cathead | 0.5540 | 0.7430 | 0.3430 | 0.0880 |
| 3 | Mobile B-80 (1996) | Rope and Cathead | 0.7480 | 1.1143 | 0.4000 | 0.1300 |
| 3 | Mobile B-80 (2000) | Rope and Cathead | 0.6120 | 0.6860 | 0.4860 | 0.0480 |
| 4 | CME 750 | Automatic | 0.8660 | 1.2000 | 0.7430 | 0.0620 |
| 5 | CME 170 | Automatic | 0.8710 | 1.0000 | 0.6286 | 0.0770 |
| 6 | CME 75 (1996) | Automatic | 0.8170 | 0.8857 | 0.7143 | 0.0460 |
| 6 | CME 75 (2000) | Automatic | 0.7870 | 0.8290 | 0.7430 | 0.0180 |
| 7 | CME 75 | Wire Line | 0.4980 | 0.6570 | 0.4286 | 0.0380 |
| 8 | BK-66 (1996) | Automatic | 0.7080 | 0.7710 | 0.6280 | 0.0280 |
| 8 | BK-66 (2000) | Automatic | 0.6860 | 0.8000 | 0.5430 | 0.0420 |
| 9 | CME 55 | Automatic | 0.8530 | 0.9140 | 0.8280 | 0.0800 |
| 10 | CME 75 | Automatic | 0.9460 | 1.0286 | 0.8857 | 0.0210 |
| 11 | CME 55 (1996) | Automatic | 0.8540 | 1.0600 | 0.7430 | 0.0800 |
| 11 | CME 55 (1999) | Automatic | 0.8100 | 0.8286 | 0.7143 | 0.0470 |
| 12 | Saitech GH3 | Rope and Cathead | 0.7545 | 0.9140 | 0.5714 | 0.0610 |
| 13 | Saitech GH3 | Rope and Cathead | 0.6970 | 0.8286 | 0.5143 | 0.0560 |
| 14 | Saitech GH3 | Rope and Cathead | 0.7632 | 0.8571 | 0.6571 | 0.0380 |
| 15 | CME 75 (1996) | Automatic | 0.5830 | 0.6571 | 0.5429 | 0.0160 |
| 15 | CME 75 (1996) | Automatic | 0.6450 | 0.8000 | 0.4286 | 0.0530 |
| 16 | Mobile B-61 | Rope and Cathead | 0.6630 | 0.8280 | 0.5710 | 0.0480 |
| 17 | Mobile B-57 | Automatic | 0.7550 | 0.9710 | 0.5710 | 0.0470 |
| 18 | Mobile B-80 | Automatic | 0.7040 | 0.8570 | 0.6290 | 0.0460 |
| 19 | CME 55 | Rope and Cathead | 0.6910 | 0.8290 | 0.5710 | ------- |
| 20 | BK-81 | Automatic | 0.8370 | 1.0570 | 0.6850 | 0.0570 |
| 21 | CME 850 | Automatic | 0.6270 | 0.7140 | 0.5710 | 0.0400 |
| 22 | Terramec 1000 | Rope and Cathead | 0.6370 | 0.7710 | 0.4570 | 0.0670 |
| 23 | CME 750 | Automatic | 0.6660 | 0.7140 | 0.6000 | 0.0280 |
| 24 | CME 850 | Automatic | 0.8200 | 0.9430 | 0.6290 | 0.0420 |
| 25 | Diedrich D-120 | Automatic | 0.8880 | 1.0570 | 0.6860 | 0.0800 |
| 26 | Diedrich D-120 (2001) | Automatic | 0.4600 | 0.7140 | 0.3140 | 0.0870 |
| 26 | Diedrich D-120 (2001) | Automatic | 0.8000 | 0.9430 | 0.6860 | 0.0540 |



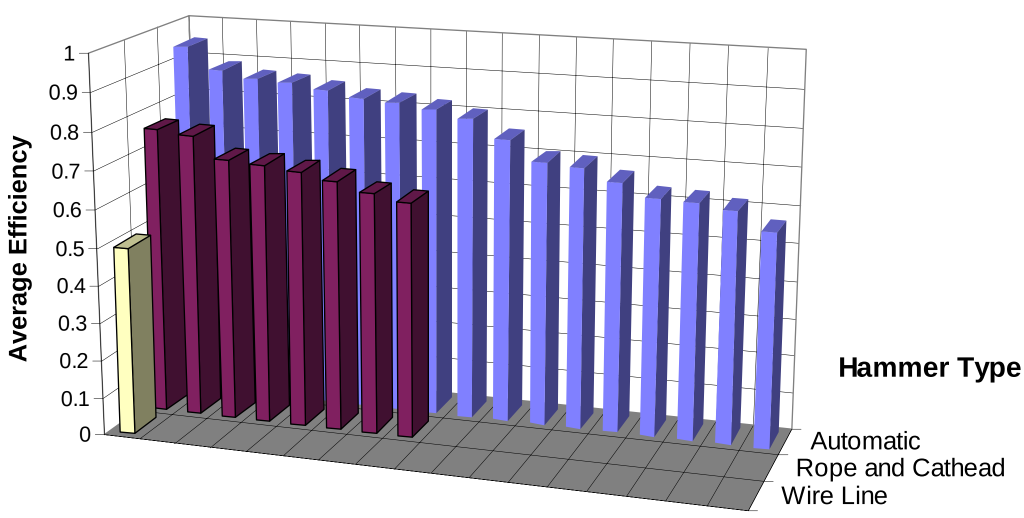
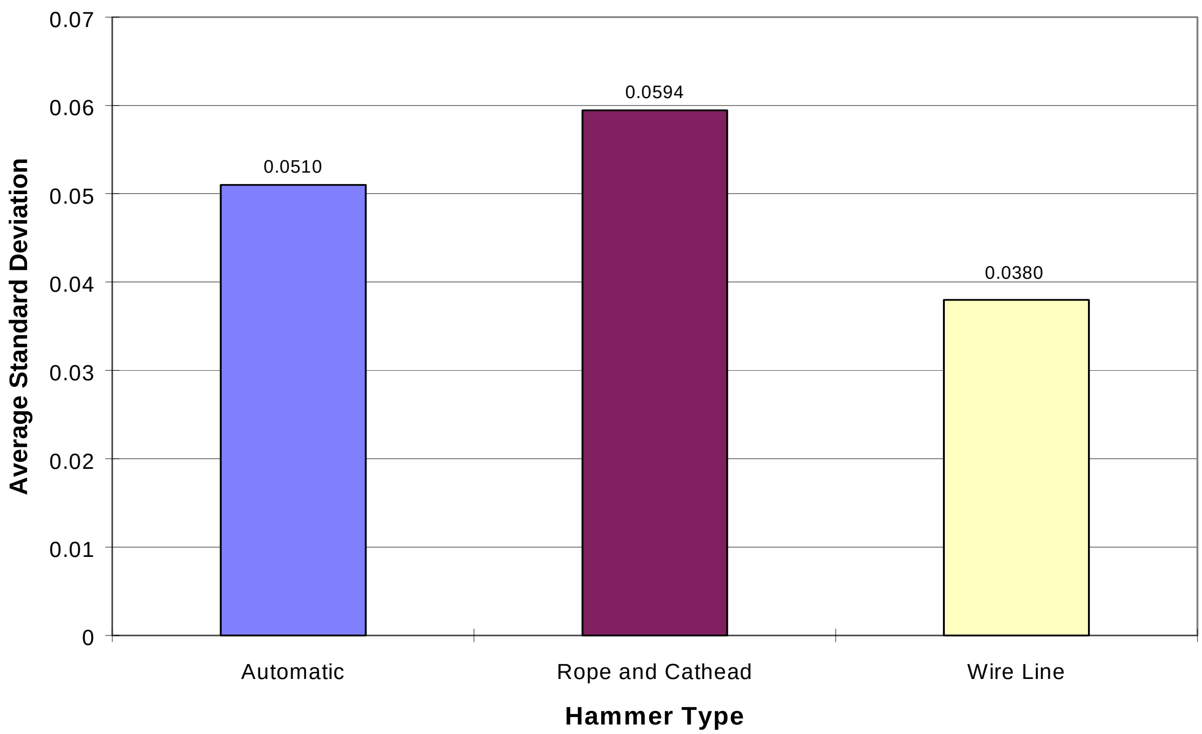




Figure 3, Average Hammer Efficiencies



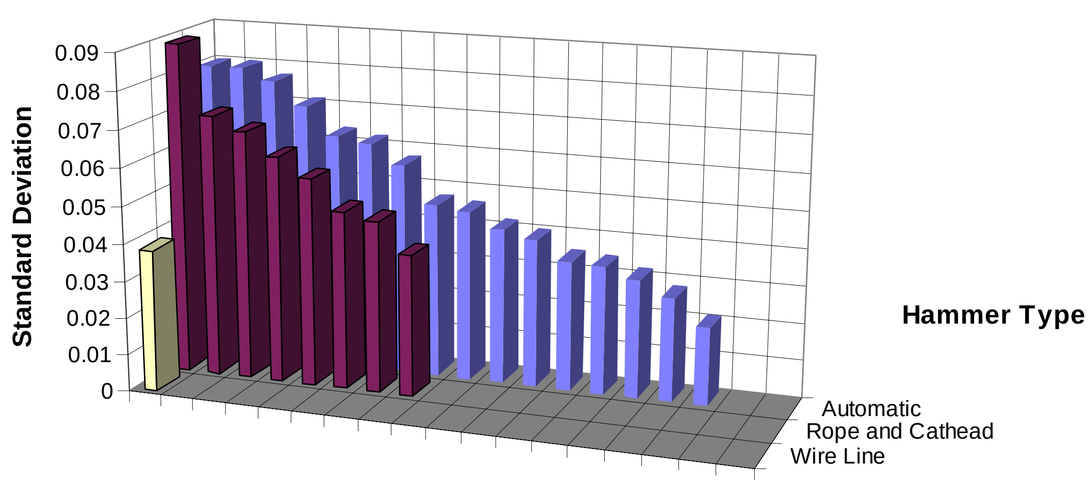




Figure 4, Standard Deviations

Seven hammers were measured as long as 4 years later to determine if the measured energy had changed. The measurements are presented in Table 3 below.

Table 3. Energy Measurement Re-test Results

| Rig No. | Make and Model | Hammer type | Average Efficiency | Maximum Efficiency | Minimum Efficiency | Std. Dev. |
|---|---|---|---|---|---|---|
| 2 | Mobile B-53 (1996) | Rope and Cathead | 0.5820 | 0.7430 | 0.3430 | 0.0530 |
| 2 | Mobile B-53 (2000) | Rope and Cathead | 0.5540 | 0.7430 | 0.3430 | 0.0880 |
| 3 | Mobile B-80 (1996) | Rope and Cathead | 0.7480 | 1.1143 | 0.4000 | 0.1300 |
| 3 | Mobile B-80 (2000) | Rope and Cathead | 0.6120 | 0.6860 | 0.4860 | 0.0480 |
| 6 | CME 75 (1996) | Automatic | 0.8170 | 0.8857 | 0.7143 | 0.0460 |
| 6 | CME 75 (2000) | Automatic | 0.7870 | 0.8290 | 0.7430 | 0.0180 |
| 8 | BK-66 (1996) | Automatic | 0.7080 | 0.7710 | 0.6280 | 0.0280 |
| 8 | BK-66 (2000) | Automatic | 0.6860 | 0.8000 | 0.5430 | 0.0420 |
| 11 | CME 55 (1996) | Automatic | 0.8540 | 1.0600 | 0.7430 | 0.0800 |
| 11 | CME 55 (1999) | Automatic | 0.8100 | 0.8286 | 0.7143 | 0.0470 |
| 15 | CME 75 (1996) | Automatic | 0.5830 | 0.6571 | 0.5429 | 0.0160 |
| 15 | CME 75 (1996) | Automatic | 0.6450 | 0.8000 | 0.4286 | 0.0530 |
| 26 | Diedrich D-120 (2001) | Automatic | 0.4600 | 0.7140 | 0.3140 | 0.0870 |
| 26 | Diedrich D-120 (2001) | Automatic | 0.8000 | 0.6860 | 0.9430 | 0.0540 |

Hammer energies varied an average of approximately 5.4% between tests, with hammers tending to perform less efficiently over time. The exception was Rig #26, a Diedrich D-120, which was nearly new at the time of the first test. The average hammer efficiency for this automatic hammer was only 46% during the initial test, which was much lower than expected. The hammer appeared to be in good condition but was taken apart, cleaned and tested again several months later because of concern over the low measured energy. The hammer's average energy during the second test was 80%, the anticipated value for this type of hammer.

**Discussion of Results**

The results of the measurements indicate that hammer energies can vary greatly even among the same hammer type. In general, automatic hammers averaged the highest energies at approximately 74% of theoretical. This energy was lower than expected (typically 80-85%) for automatic hammers. In addition, automatic hammers on average had a slightly lower standard deviation than rope and cathead hammers, which was expected.

Rope and cathead hammers were closest to 60% without going under, as should be the case, since the $N_{60}$ is mostly based on rope and cathead data. It should be noted however that rope and cathead hammers can be significantly effected by operator errors. A good example of this is the hammer on Rig #3 (Mobile B-80), which had a standard deviation of 13% during the initial test and only 4.8% during the second test. It was learned that the initial operator had been fired for incompetence. The only wireline tested, indicated the lowest energy (49%), well below the anticipated 60% value used in the standard equations. ASTM standards do not consider a wireline system acceptable for valid SPT data.

The data shows that delivered energy changes over time can be moderate, on the order of 2-13% percent for the tested hammers. One new automatic hammer, shown in Table 3 and discussed earlier, was tested and found to have a very low energy transfer. No visible indication showed evidence of this condition. The hammer was disassembled and mud was found caked on the inside. After cleaning, the hammer was re-tested and found to deliver nearly 80% of theoretical energy. The re-tested hammer performed within the expected averages and standard deviations of automatic hammer systems.

**Calibration Procedure**

The N-value is calibrated to the average measured energy of the hammer as follows (after Seed et. al., 1985):

Calculate the energy Transfer Efficiency, $ER_i$:

$$ER_i = \frac{E_i}{E^*}$$

Where $E_i$ = measured energy transferred and $E^*$ = maximum potential energy (350 ft-lbs).

Calculate the Correction Factor, $C_{60}$:

$$C_{60} = \frac{ER_i}{60\%}$$

Adjust N-value to a hammer delivering 210 ft-lbs, 60% efficiency:

$$N_{60} = NC_{60}$$

The $N_{60}$ is the calibrated value used for design correlations with strength, bearing capacity, unit weight, liquefaction potential, etc.

**Conclusions**

UDOT has conducted a series of SPT hammer energy measurements on a number of hammers using the PDA to correct the results of the SPT test. The results have been used in calibrating the N-value derived from the SPT sampling procedure in order to provide a better correlation in developing soil properties for geotechnical design.

The measurements made by UDOT indicate that SPT hammer energies can vary widely even within similar hammer types. Automatic hammers were found to be the most consistent in the blow-to-blow energies indicated by the lowest standard deviation. Rope and cathead hammers measured energies in the 60%-70% range where they are expected to be, however, consistency was slightly lower than the automatic hammers. The average energy (74%) for the automatic hammers was lower than the expected 80-85% range. The lowest average measured energy for an automatic hammer was approximately 55% (excluding the mud-caked hammer discussed earlier). Results of engineering calculations could be very unconservative if an energy value of 80-85% is assumed for low energy automatic hammers. Only one wireline system was measured and found to have the lowest average delivered energy. UDOT does not allow wireline systems.

Measurements of SPT hammer energies in accordance with the force velocity method (see ASTM D 6066-96) is recommended. UDOT has found that energies can vary widely, even between the same make and model of hammer. Longitudinal studies of 7 hammers indicate that hammers can change over time. Periodic testing of SPT hammer energy is recommended. One example of a poorly operating automatic hammer was encountered. No obvious evidence of this poor performance was noticeable without the PDA measurements, thus keeping hammers well maintained is always good practice.

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