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SPT Automatic Hammer Efficiency Revisited

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SPT AUTOMATIC HAMMER EFFICIENCY REVISITED

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ABSTRACT

Automatic SPT hammers typically provide more transferred energy to drill rods than traditional safety hammers. This results in lower measured blow-counts from automatic hammers when compared to safety hammers. To eliminate such deviations in blow-counts, quality assurance for licensing new generation nuclear power plants requires that SPT energy measurements be made for each hammer used so that blow-counts can be corrected and be appropriately used in foundation design. A series of SPT hammer energy measurements was conducted on automatic hammers using a pile driving analyzer and employing the force velocity method to measure the actual energy transferred into the system. This paper reports the results of measurements for several such subsurface investigations. Altogether, over 220 energy measurements were made on 32 different automatic hammers. The soils ranged from soft clays to partially weathered rock, and the sampling depths ranged from a few feet to over 400 feet. The results obtained are compared to the results from the studies of Florida DOT and Utah DOT. Analysis of the 220 ETR measurements gives an overall average energy correction factor of 1.36, with high and low values of 1.46 and 1.25, respectively, obtained by applying the standard deviation.

INTRODUCTION

Quality assurance for licensing new generation nuclear power plants requires that standard penetration test (SPT) energy measurements be made for each hammer used so that N-values can be corrected to N_{60} and be more appropriately used in design. A series of SPT hammer energy measurements was conducted on automatic hammers using a pile driving analyzer (PDA). The force velocity (EFV) method was employed (ASTM D 4633-05, 2005) to measure the actual energy transferred into the system.

The quantity of energy actually transferred by the SPT hammer to the drill rods is typically expressed as an energy transfer ratio (ETR), which is the percentage of the theoretical energy transferred by the hammer drop. In theory, to drive a standard split-spoon sampler into the soil, a potential energy of 350 ft-lb per blow should be accumulated by dropping a 140-pound hammer 30 inches (ASTM D 1586-99, 1999). However, studies of ETR measurements indicated a typical energy transfer of only about 60% of this theoretical energy from a traditional safety hammer to the sampling rods (Seed et al., 1985). As a result, to account for 60% energy transfer, engineers frequently normalize recorded N-values to N_{60} using the following relationship:

$$N_{60} = N_{field}(ETR / E_{60}) \quad (1)$$

where:
E_{60} = 60% of theoretical potential energy (210 ft-lb)
N_{field} = measured N-value
ETR = energy transfer ratio of the hammer
ETR/E_{60} = hammer energy correction factor

A wide range of hammer energy correction factors has been applied to automatic hammers worldwide. Typical ETR values for automatic hammers vary between 55% and 83% in North America and between 60% and 73% in the United Kingdom, and are about 60% in China (Budhu, 2007; Clayton, 1990, in Coduto, 2001), giving hammer energy correction factors from 0.92 to 1.50. Published values of ETR by other researchers over the past two decades show a range of ETR from 60% to 90%, as summarized by Butler (1997). Florida DOT's 2004 *Soils and Foundation Handbook* requires an energy correction factor of 1.24 to be applied when calculating corrected N-values (N_{60}) if automatic hammers are used (FDOT, 2004), based on a study of ETR values by Davidson et al. (1999).

On the following pages, ETR measurements on 32 automatic hammers are presented and analyzed, and the results are compared to published values. For each ETR measurement, the associated information on rig model, location, depth of sampling, soil type, rod type, recorded SPT N-value, and frequency of hammers blows is provided.

ENERGY TRANSFER RATIO MEASUREMENTS

In this study, the energy measurements were performed in accordance with ASTM D 4633-05 (2005) using a PAK model PDA with calibrated accelerometers and strain gauges. The strain and acceleration measurements were taken on 2-foot long AW, AW-J, N3, and NW-J drill rods located on top of the drill string, immediately below the automatic hammer. The strain and acceleration signals were converted to force and velocity by the PDA, and the maximum energy transferred to the drill rod strings (EFV) was calculated using the Case method equation. EFV was obtained by integrating the force and velocity measurements over time as follows:

$$EFV = \max\{\int F(t)\,V(t)\,dt\} \qquad (2)$$

where:

EFV = transferred energy
$F(t)$ = calculated force at time t
$V(t)$ = calculated velocity at time t

The ratio of EFV to the theoretical maximum potential energy (350 ft-lb) of the hammer produced the ETR.

For this study, 32 drill rigs with automatic hammers were tested in soils ranging from soft clays to silty sand to partially weathered rock at depths ranging from a few feet to over 400 feet. The tests were carried out at four different US sites, with a total of 220 runs. Because some measurements were performed more than once on the same hammer (six hammers were tested twice and one hammer was tested three times), 40 SPT systems were analyzed, as listed in Table 1. Each type of drill rig involved and the associated number of SPT systems and tests performed are also given in Table 1. Details regarding the ETR values calculated from PDA measurements of automatic hammers for this study are provided in Table 2, which provides the corresponding information on rig model used, test location, depth of sampling, soil type, rod type, recorded SPT N-value, and frequency of hammer blows.

SPT ENERGY TRANSFER RATIO FOR AUTOMATIC HAMMERS

The ETR values calculated from the PDA measurements are rearranged in Table 3 to compare these results with those from previous studies by Florida DOT (Davidson et al., 1999) and Utah DOT (Sjoblom et al., 2002), all using automatic hammers. The average ETR value of the 220 test runs is 81.5%, while the averages by FDOT and UDOT are 79.6% and 75.5%, respectively. For this study, the standard deviation in ETR is 6.4% for the 220 runs, which compares reasonably with the 7.9% obtained by FDOT. (No standard deviation values were available from the UDOT study.) As noted earlier, the N-value correction factor for automatic hammers is obtained by dividing the ETR value by 0.60. This gives an energy correction factor of 1.36 for the average ETR value of 81.5% for this study. Applying the standard deviation of +6.4%, the high- and low-end energy correction factor values are defined as 1.46 and 1.25, respectively. Note that FDOT (2004) requires that an energy correction factor of 1.24 (equivalent to an ETR of 74.4%) be used when calculating corrected N-values (N_{60}) by automatic hammers.

For each SPT system tested, including the multiple ETR retests performed on the same drill rigs, the average ETR values are plotted in Fig. 1. Since these multiple retests took place at different times, each SPT system was considered as a single automatic hammer while interpreting the data. As noted earlier, seven hammers were retested in a period of 1 year; their average ETR values are presented in Fig. 2 to determine if the measured energy had changed. Only two hammers out seven performed less efficiently over time, which does not fully support the reduction trend suggested by UDOT (Sjoblom et al., 2002).

Table 1. SPT Drill Rigs with Automatic Hammers Tested

Rig	No. of Systems	No. of Tests	Rig	No. of Systems	No. of Tests
CME 45	2	8	Diedrich D50	4	20
CME 55	8	36	Failing 1500	2	30
CME 75	8	38	Fraste	2	6
CME 85	1	5	Mobile B57	3	15
CME 550	3	21	Mobile B61	1	3
CME 750	4	25	*All Types*	*40*	*220*
CME 850	2	13			

SUMMARY AND CONCLUSIONS

This paper presents, for each of 220 ETR measurements, the associated information on rig model, location, depth of sampling, soil type, rod type, recorded SPT N-value, and frequency of hammer blows. Analysis of the 220 ETR measurements gives an overall average energy correction factor of 1.36, with high and low values of 1.46 and 1.25, respectively, obtained by applying the standard deviation. The lower bound value of 1.25 is in good agreement with the suggested correction factor of 1.24 by FDOT (2004).

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Table 2. Inclusive Summary of ETR Measurements

Rig No.	Rig Model	Location	Depth (ft)	USCS	Rod Type	Recorded N-value	Blows per Minute	ETR (%)
1	CME 45	S. Carolina	18.5	ML	-	10	-	70.6
	CME 45	S. Carolina	23.5	ML	-	9	-	71.7
	CME 45	S. Carolina	28.5	ML	-	7	-	74.3
2	CME 45	Texas	13.5	CL	AW-J	16	36.5	74.3
	CME 45	Texas	23.5	SM	AW-J	10	48.8	80.3
	CME 45	Texas	28.5	SM	AW-J	23	48.9	82.6
	CME 45	Texas	33.5	SM	AW-J	47	48.9	82.3
	CME 45	Texas	38.5	SM	AW-J	100	48.7	84.3
3	CME 55	Texas	168.5	CH	NW-J	29	53.5	86.3
	CME 55	Texas	178.5	CH	NW-J	27	53.7	86.3
	CME 55	Texas	190.0	MH	NW-J	50	53.6	87.7
4	CME 55	S. Carolina	11.0	SM	AW-J	10	54.5	74.3
	CME 55	S. Carolina	13.5	SM	AW-J	11	54.4	73.1
	CME 55	S. Carolina	18.5	SM	AW-J	10	53.6	74.0
	CME 55	S. Carolina	23.5	SM	AW-J	10	53.9	72.9
	CME 55	S. Carolina	28.5	SM	AW-J	9	54.2	75.1
	CME 55	S. Carolina	33.5	SM	AW-J	25	54.5	78.0
5	CME 55	Tennessee	13.5	-	AW-J	19	-	74.9
	CME 55	Tennessee	18.5	-	AW-J	17	-	80.0
	CME 55	Tennessee	23.5	-	AW-J	26	-	77.1
	CME 55	Tennessee	28.5	-	AW-J	22	-	76.3
	CME 55	Tennessee	33.5	-	AW-J	50/2"	-	76.0
6	CME 55	Georgia	18.5	SP-SM	N3	12	-	80.6
	CME 55	Georgia	23.5	SP-SM	N3	14	-	74.0
	CME 55	Georgia	123.5	CL-ML	N3	60	-	67.1
7a	CME 55	S. Carolina	13.5	SM	-	16	-	80.0
	CME 55	S. Carolina	18.5	SM	-	19	-	82.6
	CME 55	S. Carolina	23.5	SM	-	19	-	83.4
	CME 55	S. Carolina	28.5	SM	-	19	-	83.4
	CME 55	S. Carolina	33.5	SM	-	22	-	82.3
7b	CME 55	Georgia	33.5	SP-SM	NW-J	23	-	88.9
	CME 55	Georgia	38.5	SP-SM	NW-J	18	-	92.6
	CME 55	Georgia	43.5	CL	NW-J	9	-	88.3

Rig No.	Rig Model	Location	Depth (ft)	USCS	Rod Type	Recorded N-value	Blows per Minute	ETR (%)
	CME 55	Georgia	48.5	SP-SC	NW-J	11	-	90.3
8a	CME 55	S. Carolina	11.0	SM	AW-J	12	50.7	83.7
	CME 55	S. Carolina	13.5	ML	AW-J	14	51.1	82.9
	CME 55	S. Carolina	18.5	ML	AW-J	13	50.8	82.3
	CME 55	S. Carolina	23.5	ML	AW-J	17	50.8	82.0
	CME 55	S. Carolina	28.5	ML	AW-J	14	50.8	83.1
8b	CME 55	Georgia	78.5	SC	AW-J	15	-	90.0
	CME 55	Georgia	83.5	SM	AW-J	35	-	85.7
	CME 55	Georgia	88.5	SM	AW-J	40	-	90.0
	CME 55	Georgia	93.5	SM	AW-J	72	-	87.7
	CME 55	Georgia	98.5	SP-SM	AW-J	R	-	90.0
9a	CME 550	S. Carolina	13.5	-	-	19	-	74.3
	CME 550	S. Carolina	18.5	-	-	22	-	78.0
	CME 550	S. Carolina	23.5	-	-	37	-	79.4
	CME 550	S. Carolina	27.0	-	-	R	-	79.1
9b	CME 550	Georgia	63.5	CL-ML	AW-J	35	-	87.7
	CME 550	Georgia	68.5	CL-ML	AW-J	47	-	76.0
	CME 550	Georgia	73.5	CL-ML	AW-J	23	-	84.9
	CME 550	Georgia	78.5	CL-ML	AW-J	20	-	84.3
10	CME 550	Maryland	13.5	CH	AW	11	54.8	79.1
	CME 550	Maryland	28.5	SM	AW	50/5”	54.1	86.9
	CME 550	Maryland	43.5	SC	AW	11	54.9	91.4
	CME 550	Maryland	58.5	SM	AW	7	54.3	91.7
	CME 550	Maryland	73.5	SC	AW	19	54.4	85.4
	CME 550	Maryland	88.5	ML	AW	16	54.3	83.1
	CME 550	Maryland	103.5	ML	AW	15	54.4	79.1
	CME 550	Maryland	118.5	ML	AW	26	54.2	82.6
	CME 550	Maryland	133.5	MH	AW	19	52.5	79.1
	CME 550	Maryland	148.5	ML	AW	21	54.5	86.9
	CME 550	Maryland	163.5	ML	AW	20	54.7	72.9
	CME 550	Maryland	178.5	ML	AW	30	54.1	78.6
	CME 550	Maryland	198.5	ML	AW	23	54.5	90.6
11	CME 75	Texas	13.5	CH	NW-J	10	34.8	71.4
	CME 75	Texas	18.5	CH	NW-J	9	38.3	72.6
	CME 75	Texas	23.5	CH	NW-J	23	38.1	72.9
	CME 75	Texas	28.5	SM	NW-J	17	36.5	75.4
	CME 75	Texas	33.5	SM	NW-J	48	42.3	77.1
12	CME 75	Georgia	33.5	SC-SM	NW-J	15	-	84.3
	CME 75	Georgia	38.5	MH	NW-J	11	-	86.6
	CME 75	Georgia	43.5	SP-SC	NW-J	11	-	84.6
	CME 75	Georgia	48.5	SC	NW-J	11	-	84.6
	CME 75	Georgia	53.5	SC	NW-J	13	-	83.7
13a	CME 75	S. Carolina	8.5	ML	-	10	-	72.3
	CME 75	S. Carolina	13.5	SW/SM	-	21	-	82.0
	CME 75	S. Carolina	18.5	SW/SM	-	19	-	74.9
	CME 75	S. Carolina	23.5	SW/SM	-	15	-	74.9
13b	CME 75	Georgia	98.5	CL	NW-J	50/3”	-	75.1
	CME 75	Georgia	103.5	CL	NW-J	50/2”	-	80.3
	CME 75	Georgia	108.5	No Recovery	NW-J	R	-	77.1
14a	CME 75	S. Carolina	13.5	SM	-	51	-	72.9
	CME 75	S. Carolina	18.5	SW	-	41	-	80.9
	CME 75	S. Carolina	22.0	SW	-	50/3”	-	78.3
14b	CME 75	Georgia	138.5	CL	N3	57	-	76.6
	CME 75	Georgia	143.5	CL	N3	85/10”	-	80.9
	CME 75	Georgia	148.5	CL	N3	33	-	84.6

Rig No.	Rig Model	Location	Depth (ft)	USCS	Rod Type	Recorded N-value	Blows per Minute	ETR (%)
15	CME 75	S. Carolina	13.5	ML	-	13	-	80.9
	CME 75	S. Carolina	18.5	ML	-	12	-	79.7
	CME 75	S. Carolina	23.5	ML	-	13	-	82.0
	CME 75	S. Carolina	28.5	ML	-	16	-	81.1
	CME 75	S. Carolina	33.5	ML	-	16	-	83.4
16	CME 75	Maryland	15.0	CH	AW	7	56.2	82.3
	CME 75	Maryland	30.0	SP	AW	50/5”	55.3	82.6
	CME 75	Maryland	47.5	SM	AW-J	10	55.5	69.4
	CME 75	Maryland	60.0	SM	AW-J	5	27.7	84.6
	CME 75	Maryland	75.0	SM	AW-J	20	56.5	85.1
	CME 75	Maryland	90.0	ML	AW-J	16	53.9	82.3
	CME 75	Maryland	105.0	ML	AW-J	13	54.9	90.0
	CME 75	Maryland	120.0	ML	AW-J	10	54.4	86.3
	CME 75	Maryland	135.0	MH	AW-J	15	55.0	87.7
	CME 75	Maryland	148.5	CL	AW-J	18	56.2	86.0
17	CME 85	Georgia	13.5	SC	NW-J	8	-	77.7
	CME 85	Georgia	18.5	SP-SM	NW-J	16	-	80.9
	CME 85	Georgia	23.5	SP-SM	NW-J	44	-	86.9
	CME 85	Georgia	28.5	SP-SC	NW-J	48	-	86.9
	CME 85	Georgia	33.5	SC	NW-J	40	-	88.0
18	CME 750	Texas	18.5	ML	AW-J	21	52.7	79.4
	CME 750	Texas	28.5	SM	AW-J	11	51.8	80.6
	CME 750	Texas	33.5	SM	AW-J	33	50.5	79.7
	CME 750	Texas	38.5	SM	AW-J	47	51.0	82.0
19	CME 750	Texas	43.5	SM	AW-J	50	51.2	83.7
	CME 750	Texas	58.5	CH	NW-J	R	55.3	85.1
	CME 750	Texas	63.5	CL	NW-J	R	55.1	84.0
20	CME 750	Texas	318.5	CH	NW-J	11	54.5	86.3
	CME 750	Texas	358.5	CH	NW-J	50/3”	54.6	83.1
	CME 750	Georgia	118.5	CL-ML	NW-J	60	-	83.1
	CME 750	Georgia	123.5	CL-ML	NW-J	12	-	85.1
	CME 750	Georgia	128.5	CL-ML	NW-J	30	-	84.0
	CME 750	Maryland	16.0	CL	NW-J	19	48.0	78.3
	CME 750	Maryland	30.0	SP	NW-J	27	56.1	89.7
	CME 750	Maryland	45.0	SM	NW-J	18	52.4	90.3
	CME 750	Maryland	60.0	SM	NW-J	19	53.7	88.0
	CME 750	Maryland	75.0	SM	NW-J	20	52.8	86.6
	CME 750	Maryland	90.0	SM	NW-J	18	55.4	86.9
	CME 750	Maryland	105.0	SC	NW-J	34	55.7	88.0
	CME 750	Maryland	120.0	ML	NW-J	21	55.2	87.4
21	CME 750	Maryland	135.0	MH	NW-J	22	51.5	86.6
	CME 750	Maryland	150.0	MH	NW-J	21	55.3	88.0
	CME 750	Maryland	165.0	MH	NW-J	30	48.2	84.3
	CME 750	Maryland	180.0	SC	NW-J	20	53.8	87.7
	CME 750	Maryland	195.0	MH	NW-J	7	56.3	89.1
22	CME 850	S. Carolina	13.5	-	-	13	-	79.4
	CME 850	S. Carolina	18.5	-	-	17	-	82.6
	CME 850	S. Carolina	23.5	-	-	15	-	83.7
	CME 850	S. Carolina	28.5	-	-	12	-	84.0
	CME 850	S. Carolina	33.5	-	-	14	-	83.7
	CME 850	S. Carolina	38.5	-	-	24	-	79.7
23	CME 850	Georgia	73.5	SP-SM	AW-J	28	-	86.9
	CME 850	Georgia	78.5	SP-SM	AW-J	R	-	86.0
	CME 850	Georgia	83.5	CL	AW-J	35	-	90.0
	CME 850	Georgia	88.5	CL	AW-J	56	-	87.4

Rig No.	Rig Model	Location	Depth (ft)	USCS	Rod Type	Recorded N-value	Blows per Minute	ETR (%)
	CME 850	Georgia	13.5	CL	NW-J	32	-	79.1
	CME 850	Georgia	18.5	CL	NW-J	32	-	79.1
	CME 850	Georgia	20.0	CL	NW-J	71	-	78.9
24a	Diedrich D 50	S. Carolina	11.0	SM	-	30	-	72.3
	Diedrich D 50	S. Carolina	41.0	SM	-	22	-	70.9
	Diedrich D 50	S. Carolina	43.5	SM	-	25	-	74.6
	Diedrich D 50	S. Carolina	48.5	SM	-	24	-	76.3
24b	Diedrich D 50	Georgia	18.5	SC	AW-J	41	-	69.1
	Diedrich D 50	Georgia	23.5	SC	AW-J	33	-	72.0
	Diedrich D 50	Georgia	28.5	SC	AW-J	22	-	75.1
	Diedrich D 50	Georgia	33.5	SC	AW-J	17	-	73.4
	Diedrich D 50	Georgia	38.5	SC	AW-J	15	-	74.6
	Diedrich D 50	Georgia	43.5	SC	AW-J	15	-	74.9
25	Diedrich D 50	Texas	68.5	SC	AW-J	27	51.4	69.1
	Diedrich D 50	Texas	78.5	CH	AW-J	22	52.3	74.0
	Diedrich D 50	Texas	83.5	SP-SC	AW-J	20	55.4	73.4
	Diedrich D 50	Texas	88.5	SP-SC	AW-J	34	54.6	72.9
26	Diedrich D 50	Maryland	15.0	SP-SM	-	6	51.1	73.4
	Diedrich D 50	Maryland	30.0	SC	-	4	45.7	79.1
	Diedrich D 50	Maryland	43.5	CL	-	16	49.8	83.1
	Diedrich D 50	Maryland	60.0	SM	-	13	50.9	83.7
	Diedrich D 50	Maryland	75.0	SM	-	46	51.6	84.0
	Diedrich D 50	Maryland	90.0	SM	-	19	51.5	80.0
27	Failing 1500	Texas	43.5	CH	N3	14	39.9	69.7
	Failing 1500	Texas	48.5	CH	N3	11	-	71.7
	Failing 1500	Texas	53.5	CH	N3	19	-	74.0
	Failing 1500	Texas	58.5	CL	N3	18	39.8	75.1
28	Failing 1500	Maryland	13.5	CH	N3	8	42.1	69.1
	Failing 1500	Maryland	18.5	MH	N3	9	42.3	67.1
	Failing 1500	Maryland	28.5	CL	N3	23	42.5	74.6
	Failing 1500	Maryland	43.5	SM	N3	50/5”	42.7	79.1
	Failing 1500	Maryland	58.5	SM	N3	64	42.7	74.9
	Failing 1500	Maryland	73.5	SM	N3	50/5”	42.5	78.9
	Failing 1500	Maryland	88.5	SM	N3	29	42.5	74.9
	Failing 1500	Maryland	103.5	SM	N3	31	42.4	77.7
	Failing 1500	Maryland	118.5	ML	N3	21	42.5	74.3
	Failing 1500	Maryland	133.5	ML	N3	20	42.6	81.7
	Failing 1500	Maryland	148.5	MH	N3	22	42.5	78.0
	Failing 1500	Maryland	168.5	MH	N3	25	42.5	80.3
	Failing 1500	Maryland	178.5	CH	N3	21	42.6	77.1
	Failing 1500	Maryland	193.5	ML	N3	26	42.7	80.3
	Failing 1500	Maryland	208.5	MH	N3	26	42.4	78.9
	Failing 1500	Maryland	223.5	MH	N3	31	42.6	81.1
	Failing 1500	Maryland	238.5	MH	N3	32	42.4	79.4
	Failing 1500	Maryland	253.5	MH	N3	30	42.2	78.6
	Failing 1500	Maryland	268.5	SM	N3	30	42.6	82.6
	Failing 1500	Maryland	284.5	MH	N3	30	42.6	88.3
	Failing 1500	Maryland	298.5	SC	N3	32	42.7	80.6
	Failing 1500	Maryland	318.5	CH	N3	61	42.7	80.0
	Failing 1500	Maryland	338.5	ML	N3	41	42.7	80.3
	Failing 1500	Maryland	358.5	SM	N3	50/5”	42.6	78.3
	Failing 1500	Maryland	378.5	SM	N3	57	42.3	80.0
	Failing 1500	Maryland	400.0	SM	N3	44	42.7	80.9
29	Fraste	Texas	38.5	SM	NW-J	36	45.2	79.4
	Fraste	Texas	43.5	CH	NW-J	18	44.7	80.3

Rig No.	Rig Model	Location	Depth (ft)	USCS	Rod Type	Recorded N-value	Blows per Minute	ETR (%)
	Fraste	Texas	48.5	CH	NW-J	9	45.5	80.3
30	Fraste	Georgia	13.5	SP-SC	NW-J	33	-	78.0
	Fraste	Georgia	18.5	SP-SC	NW-J	32	-	79.4
	Fraste	Georgia	23.5	SP	NW-J	22	-	79.1
31	Mobile B 57	S. Carolina	11.0	SM	-	15	-	86.6
	Mobile B 57	S. Carolina	13.5	SM	-	14	-	85.1
	Mobile B 57	S. Carolina	18.5	SM	-	15	-	86.0
	Mobile B 57	S. Carolina	23.5	SM	-	15	-	87.4
	Mobile B 57	S. Carolina	28.5	SM	-	14	-	87.4
32a	Mobile B 57	Texas	33.5	SM	NW-J	20	35.7	93.7
	Mobile B 57	Texas	38.5	SM	NW-J	65	45.0	102.6
	Mobile B 57	Texas	48.5	CH	NW-J	9	50.7	107.4
	Mobile B 57	Texas	53.5	CH	NW-J	9	39.7	98.3
	Mobile B 57	Texas	58.5	CH	NW-J	15	21.9	90.3
32b	Mobile B 57	Texas	28.5	ML	NW-J	10	24.2	85.7
	Mobile B 57	Texas	33.5	ML	NW-J	6	21.5	83.4
	Mobile B 57	Texas	38.5	SM	NW-J	32	25.5	87.4
	Mobile B 57	Texas	43.5	CH	NW-J	12	22.2	86.3
	Mobile B 57	Texas	48.5	CH	NW-J	8	23.1	88.6
32c	Mobile B 61	Texas	88.5	CH	NW-J	20	30.1	97.7
	Mobile B 61	Texas	93.5	CH	NW-J	15	29.3	94.0
	Mobile B 61	Texas	98.5	CH	NW-J	14	29.5	96.6

Notes:
Rig No.7a was tested on 5/26/2006, and rig No.7b was retested on 2/7/2007.
Rig No. 8a was tested on 6/5/2006, and rig No. 8b was retested on 10/20/2006.
Rig No. 9a was tested on 4/10/2006, and rig No. 9b was retested on 2/7/2007.
Rig No. 13a was tested on 8/5/2006, and rig No. 13b was retested on 12/20/2006.
Rig No. 14a was tested on 6/6/2006, and rig No. 14b was retested on 3/8/2007.
Rig No. 24a was tested on 5/10/2006, and rig No. 24b was retested on 1/17/2007.
Rig No. 32a was tested on 12/8/2006, and, following repairs on the hammer housing, the hammer was retested as rig No. 32b on 12/16/2006. The same hammer was placed on rig No. 32c on 12/17/2006 and was retested.

Table 3. Summary of Automatic Hammer ETR for each Test

For Each Test	This Study			FDOT[1]			UDOT[2]		
Rig	No. of Tests	μ (%)	σ (%)	No. of Tests	μ (%)	σ (%)	No. of Tests	μ (%)	σ (%)
BK	-	-	-	-	-	-	9	76.2	-
CME	146	82.0	5.4	101	80.1	8.0	39	78.0	-
Diedrich	20	75.3	4.5	12	76.0	5.3	9	71.6	-
Failing 1500	30	77.6	4.4	-	-	-	-	-	-
Fraste	6	79.4	0.9	-	-	-	-	-	-
Mobile	18	91.4	6.8	-	-	-	9	69.4	-
All types	220	81.5	6.4	113	79.6	7.9	66	75.5	-

μ = average ETR for each test (%); σ = standard deviation of ETR for each test (%)
Notes:
[1] Florida DOT reports ETR values of automatic hammers obtained by using 14 drill rigs: 2 CME 45, 6 CME 55, 3 CME 75, 1 CME 85, and 2 Diedrich D50.
[2] Utah DOT reports ETR values of automatic hammers obtained by using 17 drill rigs: 2 CME 55, 3 CME 75, CME 170, 2 CME 750, 2 CME 850, 1 BK-66, 1 BK-81, 1 Mobile B53, 1 Mobile B57, 1 Mobile B80, and 2 Diedrich D120. Each rig was tested at three depths. Five drill rigs were retested over time.
Source: Biringen and Davie (2008)

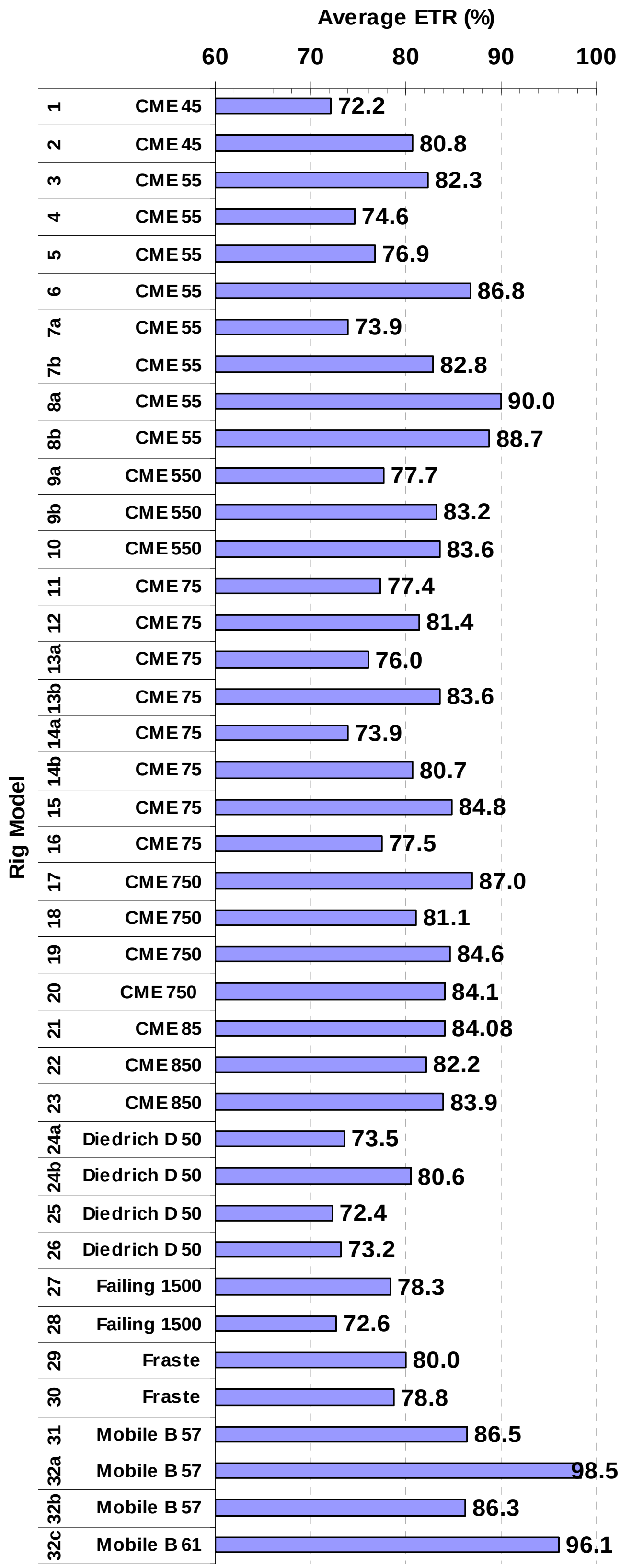

Fig. 1. Average ETR for each SPT system.

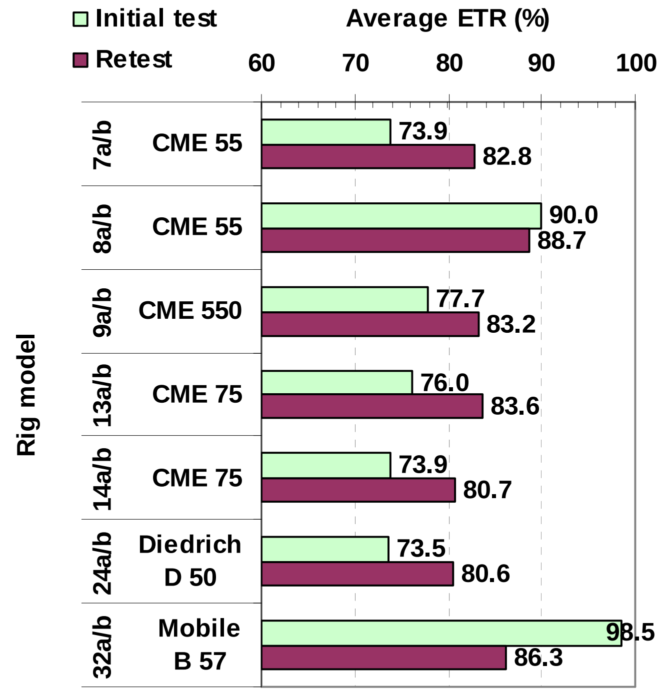

Fig. 2. ETR from retest measurements.