SPT Hammer Energy Ratio versus Drop Height

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Abstract: Automatic trip hammers have advantages for standard penetration test (SPT) of consistent drop height and low friction loss during hammer fall. These advantages, however, generate high energy transfer ratios (ER), typically about 90%. This efficiency causes lower sensitivity and higher energy correction coefficients, C_E. To reduce ER and C_E and to increase the sensitivity of SPT conducted at the Wildlife Liquefaction Array (WLA) and the Garner Valley Downhole Array, instrumented Network for Earthquake Engineering Simulation sites, a 127 mm (5.00 in.) long sleeve was placed in the hammer mechanism to reduce the drop height from 762 mm (30 in.) to 635 mm (25in.). To calibrate the energy for these drop heights, measurements were made for a series of SPT tests in Borehole X2 at WLA on November 21, 2003. For these SPT, sleeves were inserted with lengths of 50 mm (2 in.), 127 mm (5 in.) 177 mm (7 in.), and no sleeve. Resulting drop heights were 762 mm (30 in.), 711 mm (28 in.), 635 mm (25 in.), and 584 mm (23 in.). Results indicate that: (1) ER increases with rod length as expected; (2) corrections for rod length, C_R, increased with rod length in accordance with C_R published in 2001 by Youd et al.; and (3) for lengths greater than 6 m, ER increased approximately linearly with drop height. Average ER_{30} [ER based on a 762 mm (30 in.) drop height] were 43% for a 584 mm (23 in.) drop, 60% for a 635 mm (25 in.) drop, 84% for 711 mm (28 in.) drop, and 89% for a 762 mm (30 in.) drop.

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Introduction

The standard penetration test (SPT) is widely used for measurement of soil penetration resistance and subsequent correlation with soil properties such as relative density, shear strength, bearing capacity, and liquefaction resistance. Over the years, the SPT has been improved through standardization and measurement of energy transferred from the hammer to the drill rod. From the latter measurements, energy ratios (ER) are determined for correction of N values to a standard ER of 60%. The development and wide deployment of automatic trip hammers has improved test consistency and eliminated operational variables that previously plagued the test such as maintaining a constant drop height and creating near frictionless hammer fall. These hammers generally have high efficiency, ER$\approx$90%, however, which has two disadvantages: (1) Test sensitivity is inversely proportional to efficiency; and (2) a high correction factor, C_E, is required to correct measured penetration resistance to N_{60}, where

$$C_E = \mathrm{ER}_m/60 \tag{1}$$

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$$N_{60} = C_E N_m \tag{2}$$

where N_m=measured SPT resistance in the field in blows per 300 mm (1 ft). For an ER of 90%, C_E=1.5. Because N_m is measured in whole integers, the precision with which N_{60}, and the corrected blow count, $(N_1)_{60}$, can be calculated and the sensitivity of the test decreases with increasing ER. This lower precision and sensitivity may not be important for stiff or dense soils with corrected blow counts, $(N_1)_{60}>20$; but the lower precision may be very important for loose or soft soils characterized by $(N_1)_{60} < 15$.

The writers became concerned with the high ER of automatic trip hammers during a project to instrument the Wildlife Liquefaction Array (WLA) and the Garner Valley Downhole Array (GVDA), permanently instrumented NEES (Network for Earthquake Engineering Simulation) field sites for monitoring ground motions, pore-water pressures, and deformational behavior during future earthquakes. WLA, located in the Imperial Valley, approximately 13 km (8 mi) north of Brawley and 160 km (100 mi) east of San Diego. GVDA is located 16 km (10 mi) southwest of Palm Springs, Calif. The sediments at the two sites were thoroughly tested with both SPT and cone penetration test to characterize sediment properties and delineate sediment layer stratigraphy during preliminary geotechnical investigations and later during drilling for placement of instruments. The softer sediments at these sites typically have $(N_1)_{60}<15$. The drilling contractor (Pitcher Drilling Co., East Palo Alto, Calif.) used a Longyear auto safety hammer (Boart Longyear, Salt Lake City, Utah) (ER $\approx$90%) to conduct the SPT.

Reduction of Hammer Energy

For SPT at WLA and GVDA, the energy produced by the automatic trip hammer was mechanically reduced to increase sensitiv-

Table 1. Data Collected during SPT with Hammer Energy Measurements at WLA, November 21, 2003

Depth (m)	Drop height [mm (in.)]	LE [m (ft)]	Blows[a]	Average EMX (kN m)	Standard deviation EMX (kN m)	Average ER_{30} (%)	Standard deviation ER_{30} (%)	Average FMX (kN)	Average VMX (m/s)
2.91–3.20	635 (25)	4.57 (15.0)	5–22	0.241	0.005	50.8	1.0	142	3.63
3.84–4.12	635 (25)	5.18 (17.0)	5–19	0.267	0.011	56.2	2.3	142	4.15
4.74–5.03	635 (25)	5.79 (19.0)	8–25	0.259	0.007	54.4	1.4	142	3.54
5.66–5.94	635 (25)	7.32 (24.0)	6–26	0.285	0.008	60.0	1.6	120	3.66
6.41–6.60	584 (23)	7.92 (26.0)	1–16	0.203	0.003	42.9	0.6	103	3.12
6.61–6.73	711 (28)	7.92 (26.0)	17–26	0.340	0.005	83.4	1.0	129	3.79
6.75–6.86	762 (30)	7.92 (26.0)	26–32	0.422	0.012	88.8	2.5	133	3.93
7.39–7.77	635 (25)	8.84 (29.0)	1–14	0.278	0.003	59.4	0.4	117	3.57

[a]All tests conducted at a hammer drop rate of 24 blows/min.

ity by inserting a 127 mm (5.00 in.) long sleeve into the hammer mechanism. This insertion reduced the drop height from 762 mm (30 in.) to 635 mm (25 in.). This drop height was used for SPT at WLA and GVDA, except for the calibration tests, described herein where a variety of drop heights was deployed.

For the calibration tests, the drop height was initially set at 635 mm (25 in.), and measurements were collected from SPT at depths of 2.74 m (18 drops), 3.66 m (15 drops), 4.57 m (18 drops) and 5.49 m (21 drops) (9.0, 12.0, 15.0, and 18.0 ft, respectively). The hole was then deepened to 6.40 m (21 ft), and a 51 mm (2.00 in.) long sleeve inserted with the 127 mm sleeve to reduce the drop height to 584 mm (23 in.) for the first 16 hammer drops at that depth. The 127 mm (5 in.) long sleeve was then removed yielding a 711 mm (28 in.)drop height for the next 10 blows. All the sleeves were then removed, allowing development of full 762 mm (30 in.) drop height for the final 6 blows. The hole was then deepened to 7.3 m (24 ft) and the 127 mm (5 in.) long sleeve reinserted to recheck the ER for the 635 mm (25 in.) drop height (14 blows). Average ER and other values for this sequence of tests are listed in Table 1. All of SPT were conducted at a hammer-drop rate of 24 blows/min.

Mr. Camilo Alvarez, GRL Engineers, Inc., made hammer energy measurements and the subsequent energy calculations. The following text, excerpted from the GRL report (Job No. 038014), describes the test and calculation procedures. A copy of the GRL report, containing data from each calibration SPT, is on file at the NEES website at the University of California at Santa Barbara (http://www.nees.ucsb.edu/facilities/wla/):

SPT energy measurements were made on one automatic hammer mounted on a Longyear Faste Multidrill. Energy measurements were collected in one borehole location noted as X2. In total, six SPT energy measurement events were monitored. The soils were loose sands down to approximately 23 ft (7.0 m) and stiff clay to 24 ft (7.32 m). A Model PAK Pile Driving Analyzer (PDA) data acquisition system was used to collect and process the dynamic measurements of strain and acceleration. A 2.0-ft (0.61-m) long section of AWJ rod (subsection) was instrumented with two full bridge foil resistance strain gages and two piezoresistive accelerometers mounted approximately in the center of the rod. Because of connector difficulties, only one strain gage bridge output was recorded and processed. The data quality was good.

Analog signals from the strain gages and accelerometers were conditioned, digitized, stored and processed with the PDA. Selected output from the PDA for each recorded impact included the maximum calculated rod top force (FMX), maximum rod top velocity (VMX), and energy transfer by two methods and the hammer operating rate.

The primary purpose of GRL's testing was the measurement of energy transfer from the automatic SPT hammer to the AWJ drill rod. The PDA measurements of rod force and velocity were reviewed in the office after field testing, and then analyzed to calculate two transfer energy results: EMX and EF2. Energy transfer past the gage location, EMX, was computed by the PDA using the force and velocity records as follows:

$$\mathrm{EMX} = \int_a^b F(t)v(t)dt \quad (3)$$

The time "a" corresponds to the start of the record, which is when the energy transfer begins and "b" is the time at which energy transferred to the rod reaches a maximum value. The transferred energy calculations by the EMX method hold theoretically in these cases when the EF2 method does not, and EMX is therefore considered a more accurate and reliable representation of energy transfer from the SPT hammer.

For the EMX calculations, integration of F(t) occurred across the entire record, including secondary hammer impacts (Camilo Alvarez, private communication, 2007). Daniel et al. (2005) evaluated the influence of secondary impacts on transferred hammer energy in laboratory SPT with short rods, and suggest that secondary impacts add sufficient energy to the total transferred to make energy transfer independent of rod length. The results of the tests reported herein and those of previous investigators, from which short-rod corrections were developed, appear to disagree with the conclusion of Daniel et al. Because our tests and calculations occurred prior to the publication by Daniel et al., we did not apply their exact procedures. We suggest further exploration

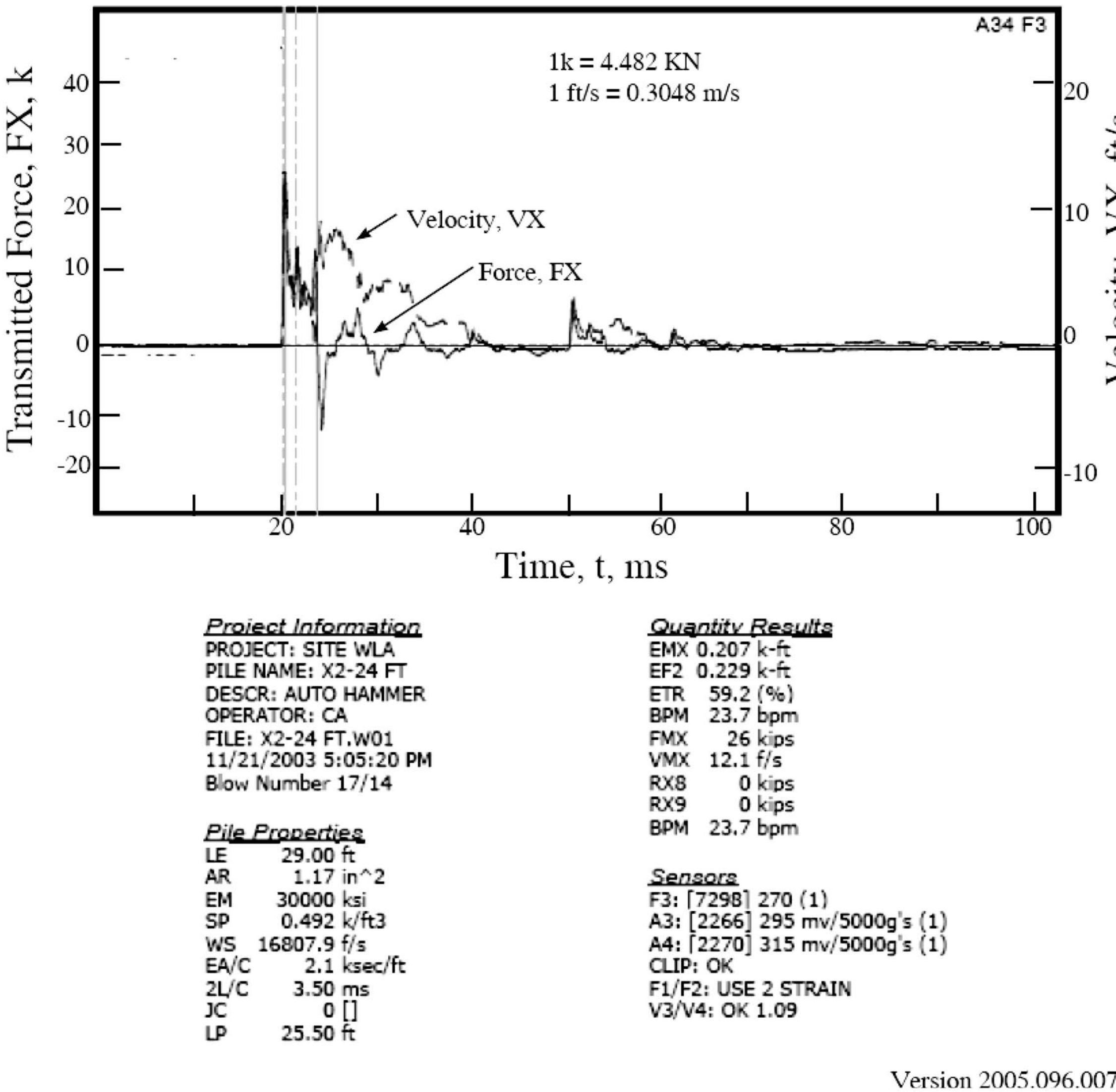

Fig. 1. Force and velocity traces from files of GRL Engineers for single hammer drop during SPT at 7.4 m (24 ft) depth, Borehole X2, WLA; drop height was 635 mm (25 in.)

of this issue is needed. Fig. 1 contains recorded force (FX) and velocity (VX) time histories from a single hammer drop, which are typical of those recorded during our tests.

Energy Ratio versus Rod Length

Fig. 2 is a graph of average hammer energy, ER_{30}, from the 635 mm (25 in.) hammer drops at each test depth versus rod length, L, where

$$L = LE - 0.61 \text{ m} \quad (4)$$

LE=length of the dynamic wave path which includes the length of AW drill rod plus the 0.61 m (2 ft) length of the split spoon sampler. ER_{30} is calculated from the following equations: Based on a 623 N (140 lb) hammer falling 762 mm (30 in.) and is calculated from

$$ER_{30} = \text{AvgEMX}/0.475 \text{ J} \quad (5)$$

where AvgEMX=average measured energy transferred during the hammer drops in a test sequence (Column 5, Table 1), and 0.475 J=potential energy of a 623 N (140 lb) hammer falling 762 mm (30 in.).

Correction coefficients for rod length, C_R, were also calculated and compared with C_R published by Youd et al. (2001). C_R were determined by dividing average ER_{30} for each test sequence with a drop height of 635 mm (25 in.) by the ER_{30} for the 8.2 m (27 ft) rod length, the length for the deepest tests in the sequence, and multiplying the result by 0.95, the C_R for 6 to 10 m (20 to 33 ft) rod lengths reported by Youd et al. (2001).

The ER_{30} curve in Fig. 2 indicates that energy transfer increased with increasing rod length and that for the longer rod lengths [greater than 5.5 m (18 ft)], ER_{30} for the 635 mm (25 in.) drop height was near 60%. C_R also increased with rod length in general agreement with the values published by Youd et al. (2001).

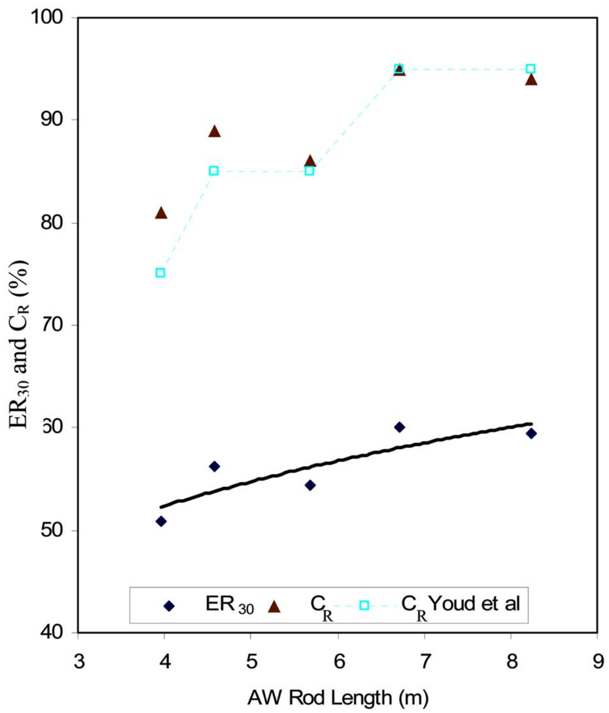

Fig. 2. Energy ratio, ER_{30}, and rod correction factor, C_R, versus rod length

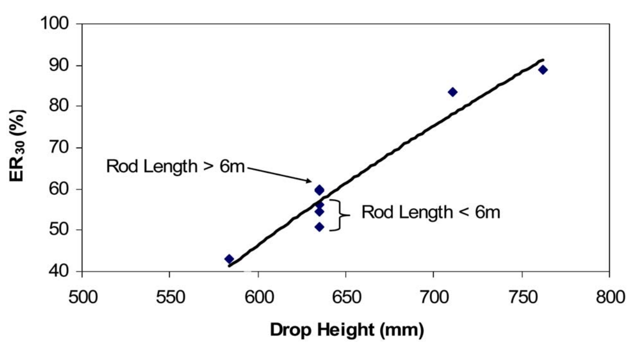

Fig. 3. Energy ratio, ER_{30}, versus drop height showing approximately linear increase of energy ratio with drop height

Energy Ratio versus Drop Height

Fig. 3 indicates an approximately linear increase of ER_{30} with drop height for rod lengths greater than 6 m (20 ft). A linear increase is expected because the potential energy of the hammer increases linearly with drop height. ER_{30} ranged from 43% for a drop height of 584 mm (23 in.), to an ER_{30} of 60% for a drop height of 635 mm (25 in.), to an ER_{30} of 83% for a drop height of 711 mm (28 in.), to an ultimate ER_{30} of 89% for a drop height of 762 mm (30 in.). The reduction of ER_{30} with drop height, however, is greater than would be predicted directly for the reduction in potential energy, indicating that efficiency of energy transfer also decreases with decreasing drop height.

Conclusions

1. The ER_{30} curve plotted in Fig. 2 indicates that ER increases with increasing rod length. For rod lengths greater than 6.0 m (20 ft), ER_{30} for a 635 mm (25 in.) drop height was near 60%. The correction for rod length, C_R, also increases with length in accordance with values published by Youd et al. (2001).
2. For the automatic trip hammer tested, ER_{30} increases approximately linearly with drop height for rod lengths greater than 6 m (Fig. 3). This linear increase is much greater, however, than the increase of potential energy, indicating that the efficiency of energy transfer increases with drop height. ER_{30} ranged from 43% for a drop height of 584 mm (23 in.), to an ER_{30} of 60% for a drop height of 635 mm (25 in.), to an ER_{30} of 83% for a drop height of 711 mm (28 in.), to an ultimate ER_{30} of 89% for a drop height of 762 mm (30 in.).

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