Measurement of Drop Height and Impact Velocity in the Brazilian SPT System

E.H. Cavalcante, B.R. Danziger, F.A.B. Danziger

Abstract. The energy efficiency in SPT is generally evaluated based on the nominal drop height. Measurements of the drop height in systems different from those used in Brazil have shown that the drop height values can be significantly different from the nominal ones, inclusively in those systems where lifting-releasing operations are automatically performed. Measurements of the drop height have been carried out in a manual lifting-releasing pinweight hammer system regularly used in Brazil. The average value of the drop height was 0.79 m, with a standard deviation of 0.03 m and a coefficient of variation of 4%. Only 6 out of the 129 measured values provided drop height values smaller than 0.75 m, which is an indication of the tendency the operator has to lift the hammer above the standard height. The average potential energy error was only 5.1%. The obtained results may be attributed to the crew experience and cannot be considered typical values of Brazilian practice. However, they do represent a condition that can be achieved in practice, provided a proper operation is undertaken. Thus, it must be seen as a goal. The impact velocity of the hammer has also been evaluated from the instrumentation. The average ratio between kinetic energy and potential nominal energy (or e_1 value) was 0.74, and 0.70 if the measured potential energy is used instead of the nominal energy. An average value of 0.99 has been obtained for the energy below the anvil and kinetic energy ratio (or e_2 value).

Keywords: *in situ* testing, SPT, instrumentation, drop height, impact velocity, energy measurement.

1. Introduction

The Standard Penetration Test (SPT) is the most common in situ test performed all over the world (Décourt *et al.*, 1988). In foundation design in Brazil, it is in most cases the only available geotechnical investigation. Despite its simplicity and robustness, it is perhaps the in situ test most dependent on the attitude of the operator. A number of factors influencing the *N* value obtained from SPT has been discussed in a number of papers (*e.g.*, Fletcher, 1965; Ireland *et al.*, 1970; De Mello, 1971; Serota & Lowther, 1973; Kovacs *et al.*, 1977, 1978; Palacios, 1977; Schmertmann & Palacios, 1979; Kovacs, 1979, 1980, 1994; Kovacs & Salomone, 1982; Riggs *et al.*, 1983; Belincanta, 1985, 1998; Skempton, 1986; Belincanta & Cintra, 1998; Décourt *et al.*, 1988, 1989; Tokimatsu, 1988; Décourt, 1989; Clayton, 1990; Matsumoto *et al.*, 1992; Morgano & Liang, 1992; Teixeira, 1993; About-Matar & Goble, 1997; Aoki & Cintra, 2000; Fujita & Ohno, 2000; Cavalcante, 2002; Odebrechet, 2003; Daniel *et al.*, 2005; Youd *et al.* 2008).

Among these papers, the one by Schmertmann & Palacios (1979) has shown that the number of blows *N* varies inversely with the energy delivered to the rod stem, to *N* equal at least 50. After some discussions concerning the need of standardization and the choice of the proper energy to be used as a reference to the *N* value (*e.g.*, Kovacs & Salomone, 1982; Robertson *et al.*, 1983; Seed *et al.*, 1985; Skempton, 1986), ISSMFE (1989) has established 60% of the theoretical free fall energy (or nominal potential energy) as the international reference. Therefore the corresponding N_{60} is obtained as:

$$N_{60} = N \frac{E}{E_{60}} \tag{1}$$

where N = measured number of blows, E = energy corresponding to N and E_{60} = 60% of the theoretical free fall energy E^*, $E^* = 474$ J.

It must be emphasized that the potential energy $E^* = 474$ J mentioned in the International Reference Procedure for SPT (ISSMFE, 1989) is related to a 63.5 kgf weight hammer and a drop height of 0.76 m, while the nominal potential energy in the Brazilian Standard (ABNT, 2001) is 478.2 J, related to a 65 kg mass hammer and a drop height of 0.75 m. The difference between the potential nominal energies of the International Reference and that of the Brazilian Standard is only 1%.

Décourt (1989) and Kulhawy & Mayne (1990) have summarized the factors affecting the energy transmission from the hammer to the rods. According to Décourt (1989), the energy entering the rod stem (or enthru energy, E_i) can be obtained as

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$$E_i = e_1 \times e_2 \times e_3 \times E^* \quad (2)$$

where e_1, e_2 and e_3 are efficiency (or correction) factors. The efficiency factor e_1 relates the kinetic energy just before the impact to the free fall energy and is mainly dependent on the way the hammer is lifted and released. A number of researches have been carried out on this subject (*e.g.*, Kovacs *et al.*, 1977, 1978; Kovacs, 1979, 1980; Kovacs & Salomone, 1982; Skempton, 1986; Tokimatsu, 1988; Décourt, 1989). Figure 1 summarizes the results obtained from different types of equipment.

The factor e_2 is associated to the loss of energy due to the presence of the anvil (Skempton, 1986). Décourt (1989) summarizes the main existing results (Fig. 2).

The efficiency factor e_3 is related to the rod length and e_3 values smaller than 1 have been proposed (*e.g.*, Schmertmann & Palacios, 1979; Skempton, 1986) to take into account the separation between hammer and anvil for rod lengths smaller than 10 m, due to the upcoming stress wave. However, recent research (Cavalcante, 2002; Odebrecht, 2003; Daniel *et al.*, 2005; Odebrecht *et al.*, 2005; Danziger *et al.*, 2006) has shown that a number of impacts may occur in a single blow, each impact being responsible for part of the energy delivered to the rod stem. Thus, e_3 should be taken as 1 (Fig. 3).

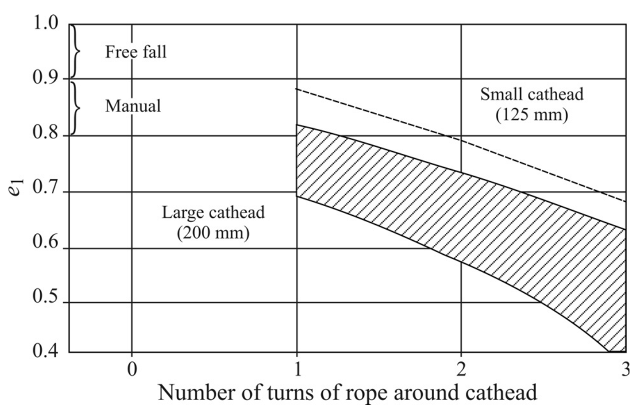

Figure 1 - Efficiency factor e_1 (adapted by Décourt, 1989 from Skempton, 1986).

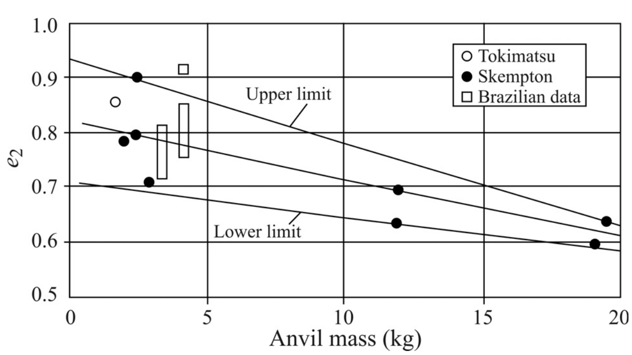

Figure 2 - Efficiency factor e_2 as a function of the anvil mass (Décourt, 1989).

Moreover, Odebrecht (2003) and Odebrecht *et al.* (2004, 2005) have shown (Fig. 4) that the potential energy resulting from the penetration ($\Delta\rho$) should be added to the nominal potential energy, which is significant in the case of soft (or loose) soils and small rod lengths.

Very few researches have measured the energy reaching the sampler, E_s, and Cavalcante *et al.* (2008) have presented results from recent researches (Fig. 5).

As shown before, the efficiency factors are related to the theoretical free fall energy, thus they are not the real ones. However, the efficiency factors are influenced by the errors associated with the non use of the real free fall energy during the test. The present paper presents a research aimed at the measurement of the potential energy of a pinweight hammer, hand lifted system commonly used in Brazil. Additionally, the impact velocity of the hammer has also been evaluated. The energy reaching the rod stem has been used to evaluate the efficiency factors based both on the theoretical free fall energy and on the measured energy as well.

2. The Free Fall Energy

The potential energy in fact used in SPT has been investigated by few researches. Riggs *et al.* (1983) gathered data from Goble & Ruchti (1981) and Kovacs *et al.* (1975) for the cathead and rope system, where two turns of rope on cathead were used. According to Riggs *et al.* (1983) the research from Goble & Ruchti (1981) involved the measurement of the impact velocity and the height of the hammer fall in more than 1500 blows. Fifteen experienced operators controlling various types of equipment participated in the

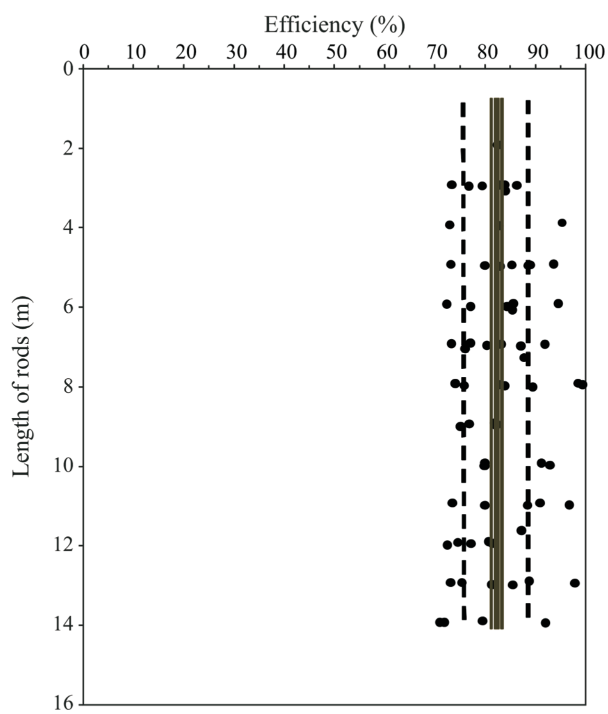

Figure 3 - Efficiency *vs.* rod length (adapted from Cavalcante, 2002; Cavalcante *et al.*, 2004).

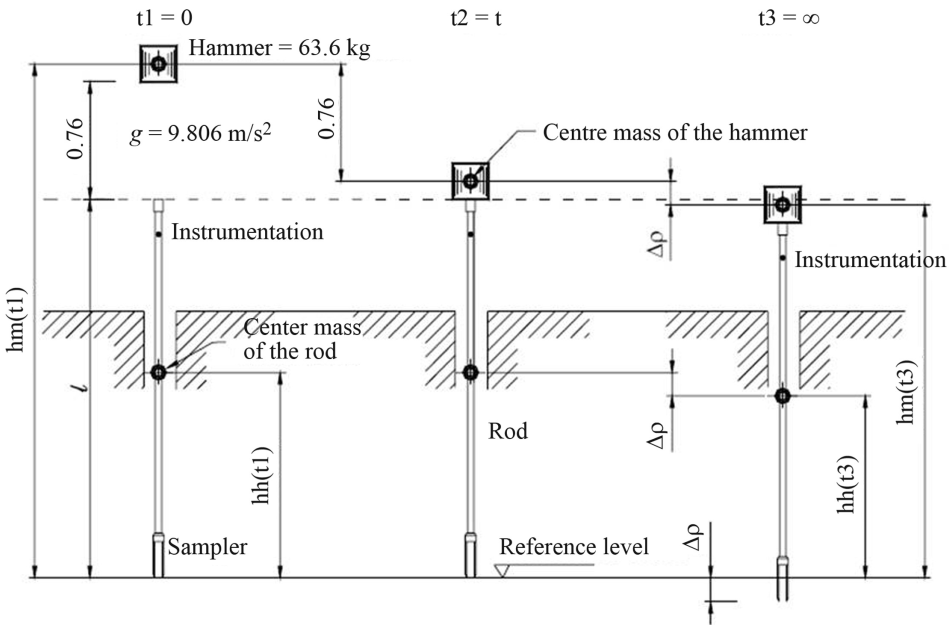

Figure 4 - Potential energy at different stages of the standard penetration test (Odebrecht, 2003; Odebrecht *et al.*, 2004, 2005).

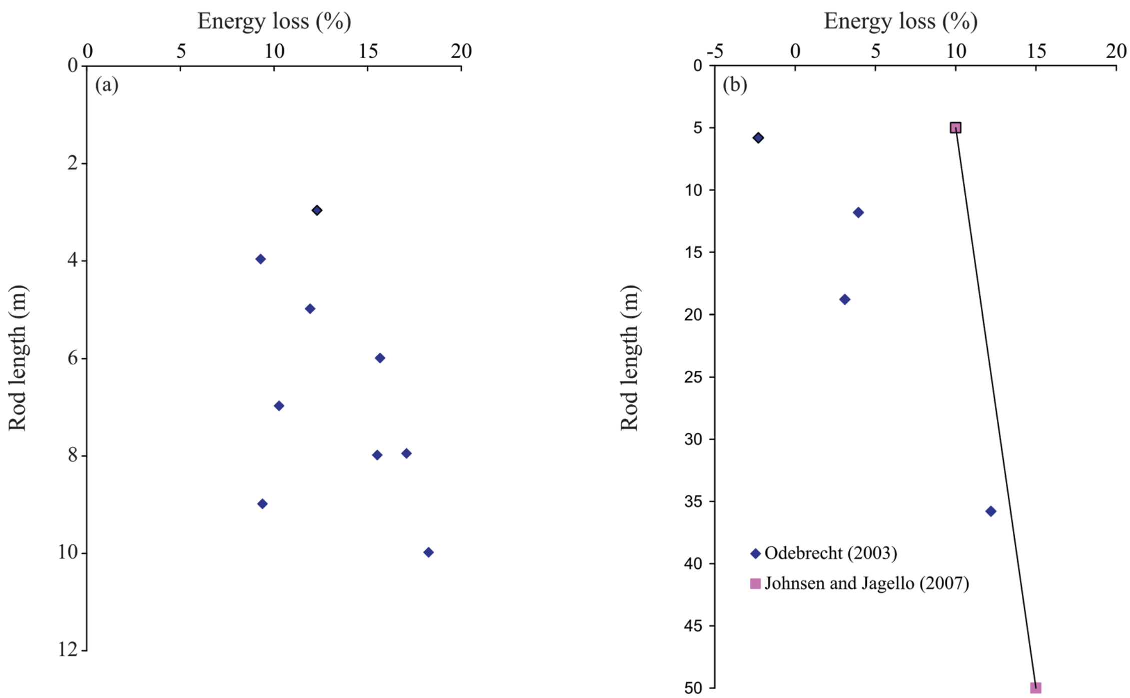

Figure 5 - Energy loss, $(E_i - E_s)/E_i$, *vs.* rod length. (a) Cavalcante *et al.* (2008), data from Cavalcante (2002); (b) Cavalcante *et al.* (2008), data from Odebrecht (2003) and general trend from Johnsen & Jagello (2007).

research. The results have shown that all the operators lifted the hammer higher than the standard 0.762 m, the average measured hammer fall being 0.817 m. The average efficiency taken from the measured impact velocity and the nominal (standard) hammer fall height was 86%. If the average efficiency had been related to the measured hammer fall height its value would have been naturally smaller. Figure 6 summarizes data obtained from Goble & Ruchti (1981) and Kovacs *et al.* (1975).

Even for the case of automatic hammers, some problems may arise on the mechanism of lifting and releasing the hammer, so that significant variations on the fall height may also occur. Kovacs (1979), for instance, presented some data from a Borros automatic free fall hammer that re-

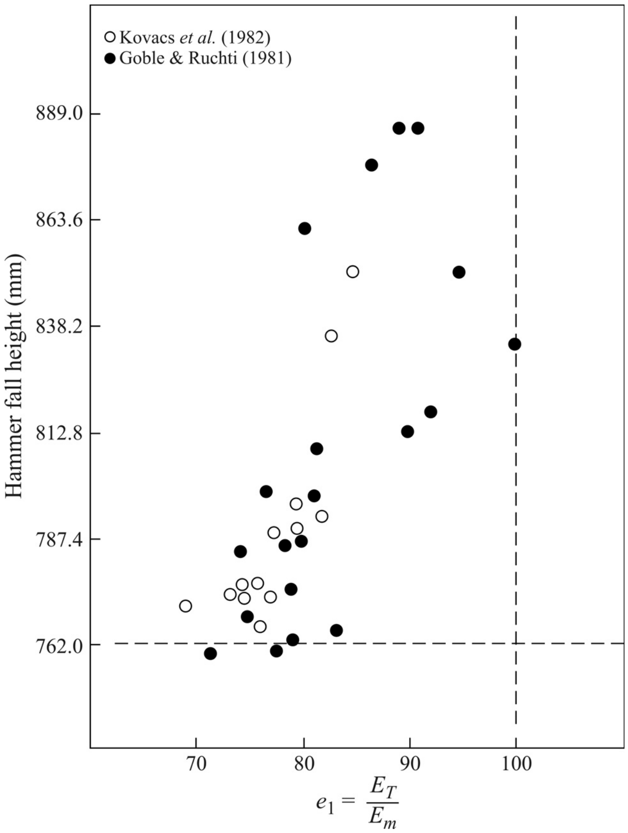

Figure 6 - Hammer fall height *vs.* efficiency, data from Goble & Ruchti (1981) and Kovacs *et al.* (1982) collected by Riggs *et al.* (1983).

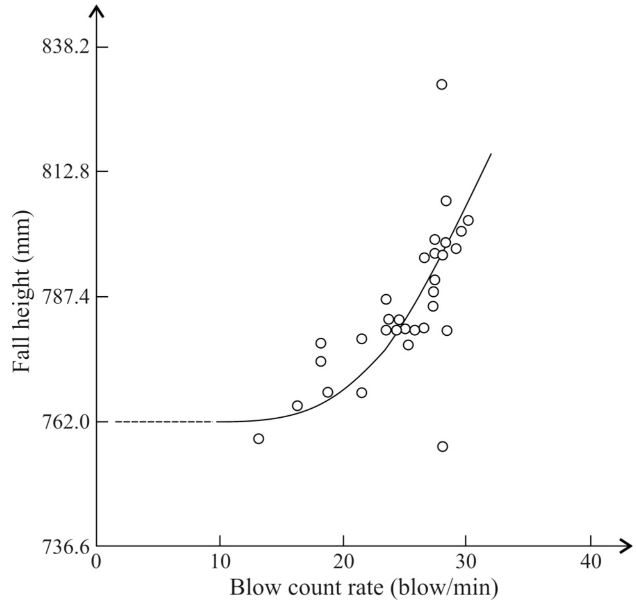

Figure 7 - Increase in fall height with blow velocity for automatic Borros free fall hammer (Kovacs, 1979).

vealed an increase in fall height when submitted to blow velocities greater than 15 blows per minute (Fig. 7).

Farrar & Chitwood (1999) have also shown that the hammer drop height is dependent on the blow count rate on an automatic hammer manufactured by the Central Mine Equipment Company (CME), as shown in Figure 8. In fact, the hammer drop height increases with the blow count rate. It must be pointed out that those authors have mentioned that the rate required to develop a 760 mm (30-inch) drop using the CME hammer is 50 to 55 blows per minute, and all drills are adjusted at the factory to provide the recommended rate. However, with time, these settings may change and should be checked. Farrar & Chitwood (1999) emphasized that if the operator fails to properly adjust the mechanical system that provides the rate, the SPT will be invalid unless the rate is recorded.

The first automatic SPT riggs have been recently introduced in Brazil (see *e.g.*, Hachich *et al.*, 2006), and a proper check of the hammer drop height is therefore very important.

3. Measurements of Hammer Impact Velocity

The systems used for measuring impact velocity in SPT hammers are based on: (i) scanners focalizing a series of reflective light strips strategically positioned at the hammer (Kovacs *et al.*, 1977, 1978; Kovacs, 1979; Kovacs *et al.*, 1981; Kovacs & Salomone, 1982); (ii) generation of an electrical pulse in parallel wires spaced by a known distance that records the hammer passage and the elapsed time during the known course (Matsumoto *et al.*, 1992); (iii) more recently, the use of radar technology with a record system based on Doppler effect (Morgano & Liang, 1992; Abou-Matar & Goble, 1997).

Figure 9 shows details of the hammer impact velocity recording system with the use of scanners and reflective light strips of contrasting colors (black and white) put on donut hammer model (Kovacs *et al.*, 1978, 1981).

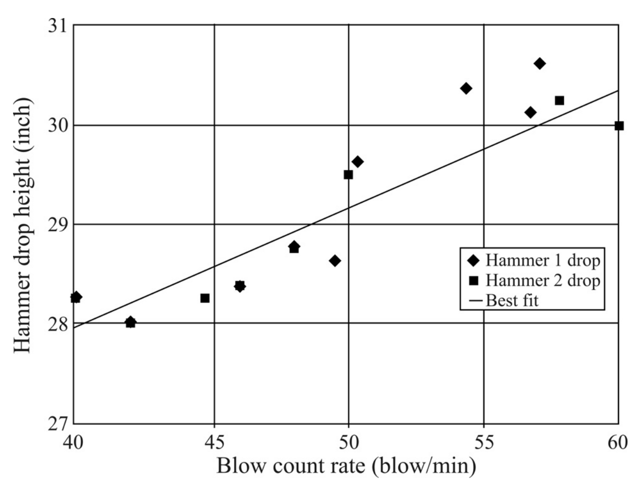

Figure 8 - Increase in fall height with blow velocity for automatic CME hammer (Farrar & Chitwood, 1999).

4. Tests Performed

SPTs have been instrumented at the district of Lapa, Rio de Janeiro, aiming at the measurement of the SPT efficiency considering both the nominal drop height and the measured values. Impact velocities have been measured in addition to the drop height. The energy just below the anvil (weight of 13 N) has been measured with a SPT Analyzer system.

A very experienced sounding crew composed of a 50 year-experience chief-operator and 2 auxiliary-operators were in charge of the SPT system.

A total of 129 hammer blows have been analyzed in 3 depths, ranging from nominal depths of 23 m to 25 m. Energy measurements below the anvil have been carried out in 96 blows. The soil nature at the tested depths consisted of a residual sand from weathered gneiss. Table 1 summarizes the measurements performed.

4.1. Drop height and impact velocity measurement system

The drop height has been measured by an equipment consisting of:

(i) a wood ruler, fixed in the rods in a way that the beginning of the scale coincided with the anvil top (Fig. 10);

(ii) an Invar ruler, manually held during the tests;

(iii) a metallic pointer, fixed at the base of the hammer, to provide a better reference for the measurements (Fig. 11);

(iv) a camera capable of filming at a speed of 30 pictures per second, placed at a level and at a distance able to properly record the blows (Fig. 12);

(v) additionally, one of the accelerometers used in connection with the energy measurements below the anvil was fixed in the hammer (Fig. 11).

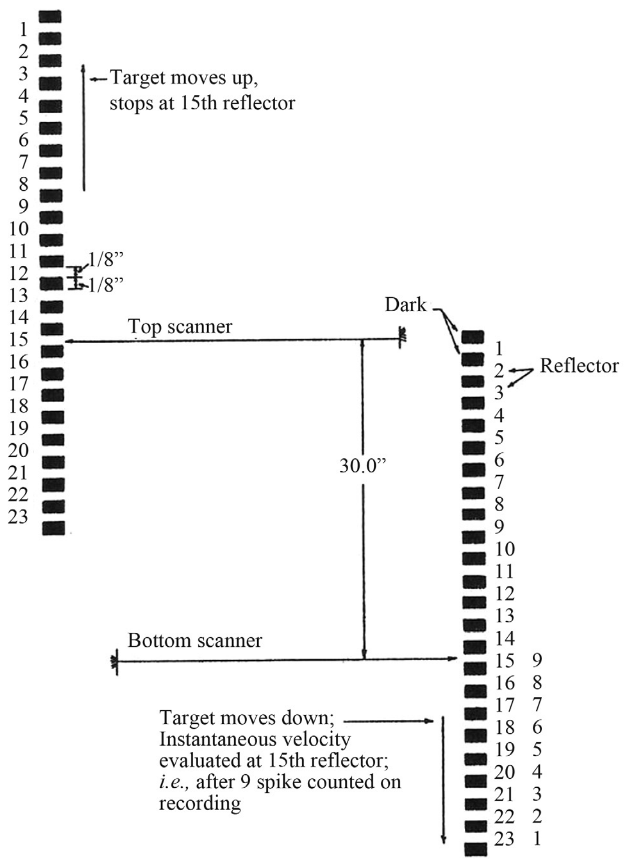

Figure 9 - Details of the reflective light strips used for the scanners to record the hammer impact velocity (Kovacs *et al.*, 1978).

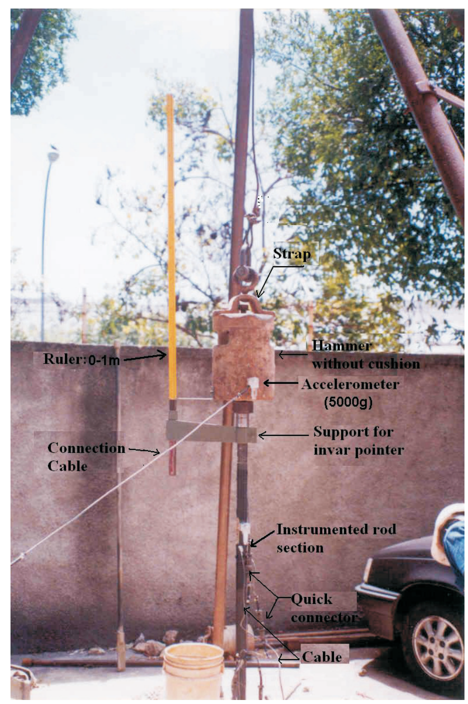

Figure 10 - Instrumentation used to measure drop height and impact velocity.

Table 1 - Measurements performed.

Nominal depth (m)	N	Rod length (m)	Number of filmed blows	Energy measured below the anvil
23	27	25.39	22	No
24	46	25.67	57	Yes
25	-*	26.80	50	Yes

*50 blows have been able to penetrate only 26 cm.

The blows have been filmed during both the operations of lifting and releasing the hammer (Figs. 13 and 14). The images have been analyzed by means of a cassette video and a video monitor. The speed of the camera has allowed an accurate definition of the drop height, *i.e.*, with the use of the commands "slow motion" and "pause" it has been possible to properly define the maximum height the hammer was lifted, following successive pictures with intervals of 0.033 s.

However, the camera speed did not allow to get the proper definition of the impact velocity. In fact, at the beginning of the releasing process, it was possible to get sharp images of successive pictures. However, as the rate increased, it was no longer possible to get the proper definition of 2 successive pictures, so from a certain time the drop rate could not be properly measured. Another method was then used to estimate the impact velocity. The drop height was divided in 3 sections, and both elapsed time and length in each section have been recorded. It has been assumed a linear velocity in each section, which corresponds to a constant acceleration. The initial velocity of each interval was taken as the final velocity of the previous interval, and the impact velocity was taken as the final velocity of the third section. An example of the obtained values is presented in Table 2 (see also Fig. 15).

In order to check the errors due to the assumed hypothesis, hammer equilibrium has been considered (Fig. 16), and Eq. (3) can be written

$$mg - F_{at} = m\frac{dv}{dt} = m\frac{d^2s}{dt^2} \tag{3}$$

where m = hammer mass, g = gravity acceleration, v = hammer velocity, s = covered distance (from hammer release), t = time (from hammer release) and F_{at} represents both the friction between the hammer guide and the anvil/rod (F_1) and also the force acting at the hammer top due to friction at the pulley (F_2).

If any friction effect is disregarded, a free fall condition is achieved, and $s = f(t)$ is a second degree equation. If F_{at} is not constant then $s = f(t)$ will be a polynomial with a degree higher than 2, and a 4[th] degree polynomial has been assumed as an approximation, according to Eq. (4).

$$s(t) = s_0 + s_1t + s_2t^2 + s_3t^3 + s_4t^4 \tag{4}$$

As doing so, one should arrive at a more approximate response of the event. Using the boundary conditions $s = 0$

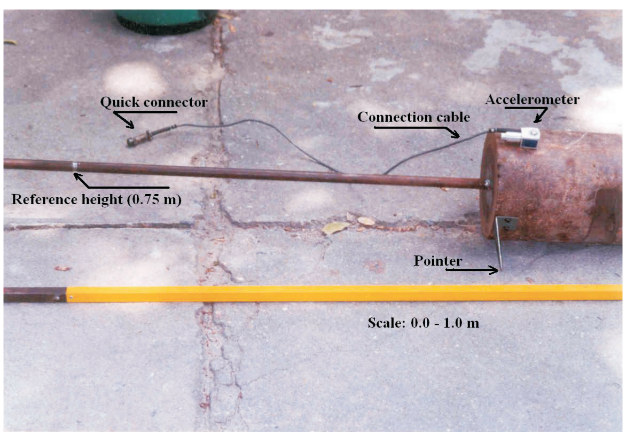

Figure 11 - Detail of the hammer, guide and part of instrumentation used to measure drop height and impact velocity.

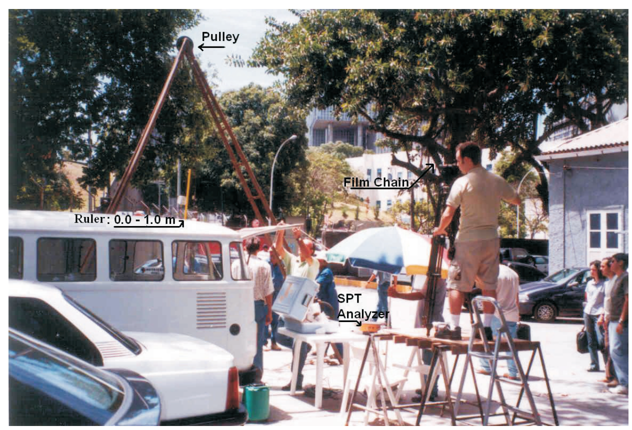

Figure 12 - System used to evaluate drop height, impact velocity and energy below the anvil.

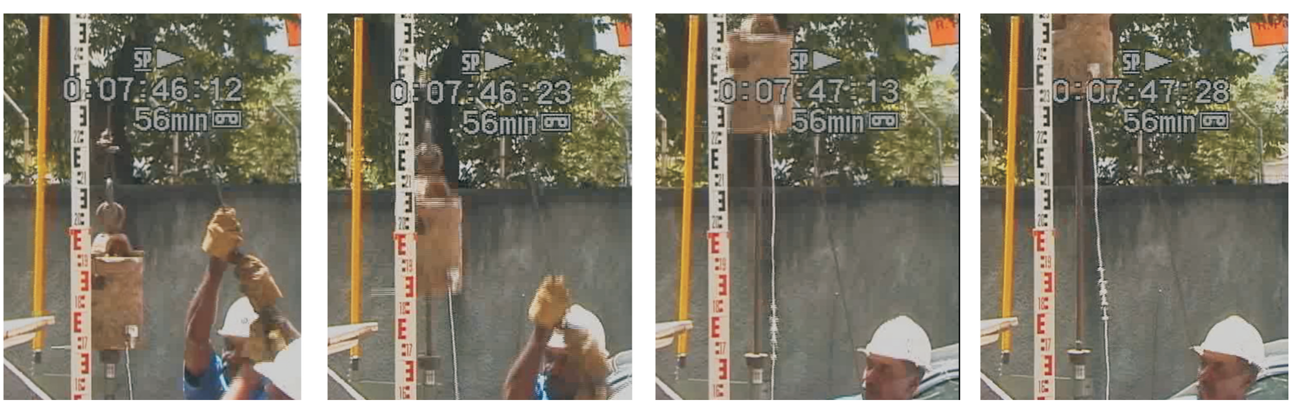

Figure 13 - Video frames during hammer lift.

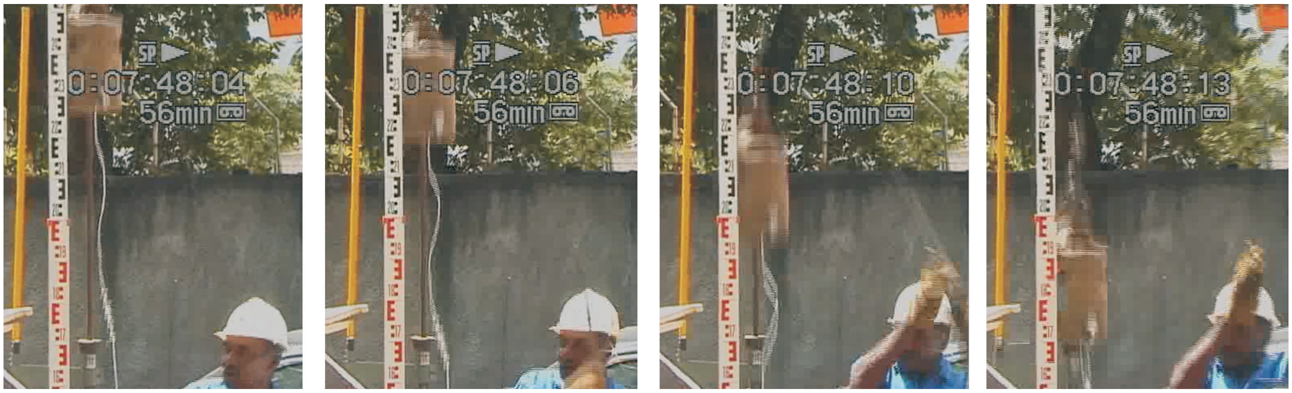

Figure 14 - Video frames during hammer fall.

Table 2 - Example of calculation of impact velocity.

Section	Length, Δh (m)	Elapsed time, Δt (s)	Initial velocity (m/s)	Final velocity (m/s)
1	0.15	0.23	0	1.30
2	0.21	0.13	1.30	1.93
3	0.44	0.17	1.93	3.25*

*Impact velocity.

for $t = 0$ and $v = 0$ for $t = 0$ the values $s_o = 0$ and $s_1 = 0$ can be respectively obtained. Thus, Eq. (4) can be simplified to

$$s(t) = s_2 t^2 + s_3 t^3 + s_4 t^4 \tag{5}$$

The use of Eq. (5) for each one of the 3 sections provides a system of 3 equations and 3 unknowns. The values included in Table 2 provide the equation

$$s(t) = 3.175t^2 - 2.141t^3 + 2.874t^4 \tag{6}$$

The velocity can then be obtained as

$$v(t) = 6.350t - 6.422t^2 + 11.496t^3 \tag{7}$$

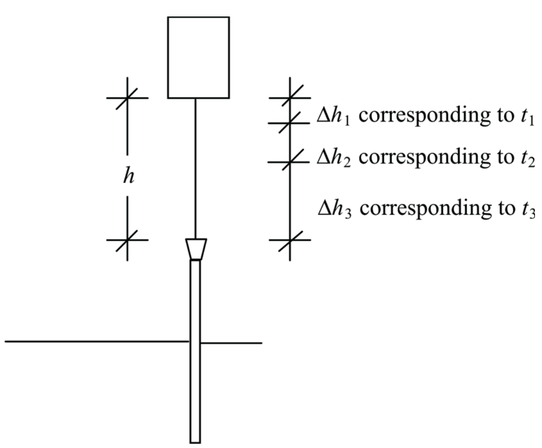

Figure 15 - Measured values used to evaluate the impact velocity.

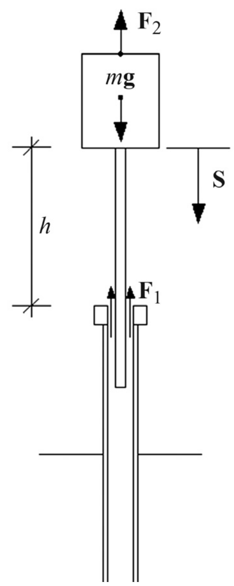

Figure 16 - Friction during hammer fall.

Eq. (7) provides the values included in Table 3, which also includes the values from the linear hypothesis (in each interval) assumption. The differences between both hypotheses are also included in the table.

As expected, the difference between both hypotheses decreases as time increases, *i.e.*, the velocity is closer to a linear behaviour approaching impact.

Table 3 - Hammer impact velocities.

t (s)	v (m/s)		Difference (%)
	Assuming linear variation in each interval	Assuming 4th degree equation for $s = f(t)$	
0.23	1.30	1.26	+3.2
0.36	1.93	1.99	-3.0
0.53	3.25*	3.27*	-0.6

*Impact velocity.

The SPT Analyzer system used to measure the energy just below the anvil has been tentatively used to measure the impact velocity, by fixing one accelerometer in the hammer, as mentioned in the previous section (see Fig. 11). However, owing to the longer interval of the fall height, nearly 400 ms, compared to the maximum time allowed by the SPT Analyzer system, 102.4 ms, it has not been possible to record the impact hammer velocity.

4.2. Test results

The histograms of drop height measured values (h) are shown in Figs. 17, 18 and 19, respectively for the 23 m, 24 m and 25 m nominal depths. The average values are included in Table 4. The corresponding values of potential energy ($E_{pot,\ meas}$) are also included in the table.

The average drop height for the 23 m nominal depth is 0.78 m, associated with a small standard deviation of 0.01 m and a coefficient of variation of 1.7%. In no case has the hammer been released at a drop height lower than 0.75 m. It must be taken into account that the first series of measurements deserved a very special attention of the crew as far as the use of the correct drop height is concerned. Due to the small difference of the drop height with respect to the nominal one, the average potential energy error was only 4.5%.

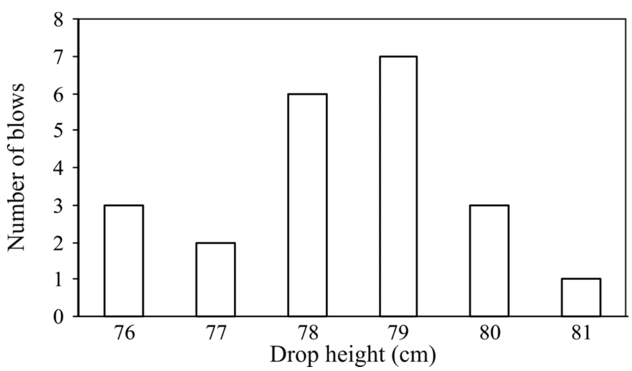

Figure 17 - Drop height values measured at 23 m nominal depth.

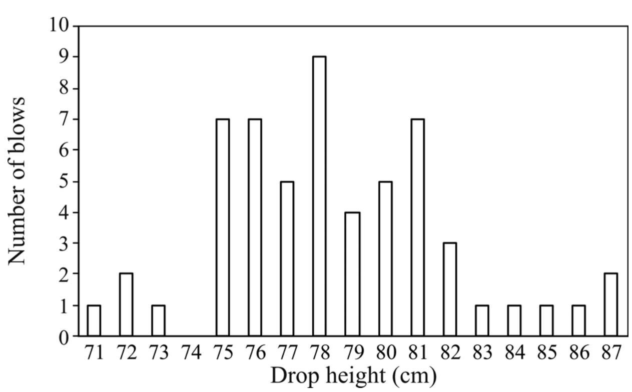

Figure 18 - Drop height values measured at 24 m nominal depth.

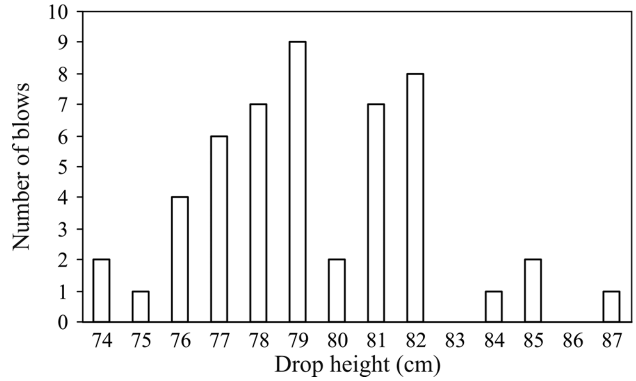

Figure 19 - Drop height values measured at 25 m nominal depth.

Similar results have been obtained for the other nominal depths (24 m and 25 m). However, the crew was asked to behave more naturally during the second and third series of measurements. As a consequence, the standard deviation and the coefficient of variation were higher at those depths (see Table 4).

If all data is now analyzed, the average value of the drop height is 0.79 m, with a standard deviation of 0.03 m and a coefficient of variation of 4%. Only 6 out of the 129 measured values provided drop height values smaller than 0.75 m, which is indeed an indication of the tendency the operator has to lift the hammer above the standard height, as shown previously for other SPT systems, as shown *e.g.* by Riggs *et al.* (1983), see Fig. 6.

The average potential energy error was only 5.1%. The very good results obtained may be attributed to the crew experience and cannot be considered typical values of Brazilian practice. However, they do represent a condition that can be achieved in practice, provided a proper operation is undertaken. Thus, it must be seen as a goal.

The average values of impact velocity (v_{imp}) and the corresponding values of kinetic energy (E_{kin}) are included in Table 5.

As a consequence of the smaller scatter of the drop height at the nominal depth of 23 m, there was a smaller scatter of the impact velocity data with respect to the other depths, as can be seen in Table 5.

The average impact velocity was 3.29 m/s, indicating a loss compared to the nominal value ($v_{imp} = \sqrt{2gh}$, h = 0.75 m) of 14.2%. If one now considers the average measured drop height value of 0.79 m, the loss in velocity is 16.4%. As the kinetic energy takes the square of the velocity, the average ratio between kinetic energy and potential nominal energy, $E_{pot,\ nom}$ (or e_1 value) is 0.74; if the measured potential energy is used, the obtained value is even smaller, about 0.70 (see Table 5). Those values are smaller than the ones included in Fig. 1, suggested by Décourt (1989).

Besides the evaluation of drop height and impact velocity, the energy below the anvil has also been measured at the nominal depths of 24 m and 25 m with a SPT Analyzer

Table 4 - Summary of drop height measurements.

Nominal depth (m)	Number of blows	*h* (m)	Standard dev. (m)	Coef. var.	$E_{pot,\ meas}$ (J)	$E_{pot,\ meas}$ error*(%)
23	22	0.78	0.01	1.7%	499.69	4.5
24	57	0.78	0.04	4.5%	500.39	4.6
25	50	0.79	0.03	3.5%	506.29	5.9
Whole data	129	0.79	0.03	3.8%	502.56	5.1

*with respect to the nominal value of 478.24 J.

system, and accelerometers and force transducers (strain-gauge based) have been used. Details of the energy measurement have been presented by *e.g.*, Cavalcante (2002), Cavalcante *et al.* (2003; 2004). The average energy values (*EFV*) are included in Table 6. Those values are lower than the ones obtained in other places in the same research, although in smaller depths (Cavalcante, 2002; Cavalcante *et al.*, 2004). In fact, those values do represent an energy ratio $EFV/E_{pot,nom}$ of 73%, smaller than the average of those other depths (see Fig. 3), with an average ratio of 0.82.

If the measured potential energy is used rather than the nominal one, *i.e.*, if one considers the energy ratio $EFV/E_{pot,meas}$, an even smaller value, 0.70, is obtained (see Table 6).

The most plausible explanation for the smaller energy ratio in the data herein reported is that smaller drop height values have been used only in the tests herein reported, due to the crew experience. Since drop height values have not been measured in the other mentioned tests, more research is needed relating the average ratio with the potential energy indeed used in the tests.

When the EFV/E_{kin} average ratio is analyzed, it can be observed that it is very close to 1, indicating a value of e_2 around 1. This value is higher than the range suggested by Décourt (1989), included in Fig. 2. In various blows the energy measured below the anvil was greater than the kinetic energy, a fact that seems inconsistent, even considering any increase of the potential energy suggested by Odebreht (2003). This has been attributed to the scatter related to the impact velocity measurements. However, the average values have shown clearly the trend of EFV/E_{kin} to be around 1, as mentioned.

5. Conclusions

Drop height and impact velocity have been measured in 129 blows in 3 nominal depths in SPTs performed in Rio de Janeiro. The first series of measurements (23 m nominal depth) deserved a very special attention of the crew as far as the use of the correct drop height is concerned, and the average drop height was 0.78 m, associated with a small standard deviation of 0.01 m and a coefficient of variation of 1.7%. In no case has the hammer been released at a drop height lower than the Brazilian standard 0.75 m. The average potential energy error was only 4.5%. The crew was asked to behave more naturally during the second and third series of measurements, and although the average drop height was only 0.01 m greater (0.79 m), the standard deviation and the coefficient of variation were higher. If the whole data is now analyzed, the average value of the drop height was 0.79 m, with a standard deviation of 0.03 m and a coefficient of variation of 4%. Only 6 out of the 129 measured values provided drop height values smaller than 0.75 m, which is indeed an indication of the tendency the operator has to lift the hammer above the standard height,

Table 5 - Summary of impact velocity measurements.

Nominal depth (m)	Number of blows	v_{impact} (m/s)	Standard dev. (m/s)	Coef. var.	E_{kin} (J)	$E_{kin}/E_{pot,\ nom}$ (%)	$E_{kin}/E_{pot,\ meas}$ (%)
23	21	3.29	0.24	7.4%	354.61	0.74	0.71
24	57	3.23	0.33	10.1%	342.44	0.72	0.68
25	50	3.35	0.29	8.7%	366.36	0.77	0.72
Whole data	128	3.29	0.30	9.3%	353.78	0.74	0.70

Table 6 - Summary of energy below the anvil measurements.

Nominal depth (m)	Number of blows	*EFV* (J)	Standard dev. (J)	Coef. var.	EFV/E_{kin}*	$EFV/E_{pot,\ nom}$	$EFV/E_{pot,\ meas}$
24	53	348.96	26.54	7.6%	1.02	0.73	0.70
25	45	348.85	20.48	5.9%	0.95	0.73	0.70
Whole data	98	348.91	23.95	6.9%	0.99	0.73	0.70

as shown for other SPT systems. The average potential energy error was only 5.1%. The very good results obtained may be attributed to the crew experience and cannot be considered typical values of Brazilian practice. However, they do represent a condition that can be achieved in practice, provided a proper operation is undertaken. Thus, it must be seen as a goal.

The average impact velocity was 3.29 m/s, indicating a loss compared to the nominal value of 14.2%. If the average measured drop height value of 0.79 m is considered, the loss in velocity is 16.4%. The average ratio between kinetic energy and potential nominal energy (or e_1 value) is 0.74; if the measured potential energy is used, the obtained value is even smaller, about 0.70.

The energy below the anvil has also been measured at the nominal depths of 24 m and 25 m. An average energy ratio of 73% has been obtained, if the potential nominal energy is considered (as the usual procedure). If the measured energy is considered, instead of the nominal one, an average energy ratio of 70% is obtained. Those values are smaller than the ones obtained in other places in the same research (Cavalcante, 2002; Cavalcante *et al.*, 2004). The most plausible explanation for the smaller energy ratio in the data herein reported is that smaller drop height values have been used only in the tests herein reported, due to the crew experience. Since drop height values have not been measured in the other mentioned tests, more research is needed in order to properly relate the average energy ratio below the anvil to the potential energy indeed used in the tests.

An average value very close to 1 (0.99) has been obtained for the EFV/E_{kin} ratio (or e_2 value).

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