Proposal of an Energy Comparison System in the SPT

G.W. Barreto, J.C.A. Cintra, N. Aoki

Abstract. This paper describes a mechanical device to compare the energy transference from the blow of a hammer to the stem referring to standardized and non-standardized equipment in Brazil. The device allows to measure the vertical displacement of a sleeve due to one or more blows of a hammer falling freely. Tests were carried out using three pieces of equipment for the SPT measurements, but only one was mounted on a tripod standardized by the NB 6484:2001 norm. Based on the displacement values, a comparative analysis of the available energies of the equipment was conducted. The efficiency of the standard tripod for the test performed without a strict control of the fall of the hammer relative to the transfer efficiency of the test performed with a strict control of the fall height was 82.5%, showing a significant influence of human factor on the results. The lowest coefficient of variation of the displacements (5.05%) was obtained for the test using mechanized equipment with an automatic hammer. From the standpoint of the available energy of the system, it is possible to use non-standard equipment by applying the correction factor (C*f*) to SPT results. Finally, static tests were performed on the sleeve and the energy transferred to the system was calculated.
Keywords: *in situ* testing, SPT, instrumentation, energy measurement.

1. Introduction

Many researchers have discussed the N value obtained from SPT and/or the energy delivered to the rod stem (*e.g.*; De Mello, 1971; Kovacs *et al.*, 1977, 1978; Palacios, 1977; Schmertmann & Palacios, 1979; Kovacs & Salomone, 1982; Robertson *et al.*, 1983; Belincanta, 1985, 1998; Belincanta & Cintra, 1998; Decourt *et al.*, 1988; Decourt, 1989; Teixeira, 1993; Aoki & Cintra, 2000; Cavalcante, 2002; Schnaid *et al.*, 2002; Schnaid *et al.*, 2004; Neves, 2004; Odebrechet, 2003; Odebrecht *et al.*, 2005; Odebrecht *et al.*, 2007; Schnaid, *et al.*, 2009; Lukiantchuki, 2012).

In Brazil, the Standard Penetration Test (SPT) is, in most cases, the only geotechnical investigation available (Cavalcante & Danziger, 2011), therefore it is indispensable for the elaboration of projects of foundations. The Brazilian norm foresees the lifting of the hammer by hand, but it allows the usage of automatic devices as long as the transferred energy has been proven.

Although, according to the norm these energies must be obtained from the usage of an instrument with load cells and accelerometers, this instrumentation is not used routinely.

On the other hand Brazilian laws and international recommendations from more developed countries suggest a conflict with the NBR 6484:2001 (ABNT, 2001) regarding the weight lifting and handling.

According to Pellenz (2005), Brazilian experts in ergonomics, when appointed as experts in labor contests, have been using the NR 17 standard published by the Brazilian Labor and Employment Ministry (Ministério do Trabalho e Emprego, 1978) and the NIOSH Method (1994) for the submission of opinions on jobs that involve the lifting and/or handling of weights. NR 17 is a norm of the Brazilian Labor and Employment Ministry, which deals with workplace ergonomics. In June 1978 the first issue of NR 17 was published, and so was the last revision in June 2007. The National Institute for Occupational Safety and Health (NIOSH) is the U.S. Federal Agency responsible for conducting research and making recommendations for the prevention of work-related injury and illness.

Merino (1996) reports the recommendations of some countries regarding the maximum weights that can be raised, which, depending on the working conditions, age and gender, are significantly lower than the weight of 637 N standardized by NBR 6484:2001. It is good to remember that the Brazilian practice of using two people to lift the weight is not appropriate once its liberation does not usually occur simultaneously, thus jeopardizing the result of the test.

As dynamic measurements of force and acceleration during the event of SPT test have not been used routinely and the hand lifting of the hammer is not compatible with the current technological stage in most countries, this paper deals with the development of a device that allows comparing the energy available in the system following the procedures adopted by the NBR 6484:2001 with other non-standard procedures in Brazil. The usage of this device would allow a more frequent application of mechanized equipment to perform SPT test, as it is entirely mechanical, easy to use, consisting of a simple assembly, with low cost and easy interpretation results.

G.W. Barreto, MSc, PhD Student, Escola de Engenharia de São Carlos, Universidade de São Paulo, 13.560-970 São Carlos, SP, Brazil. e-mail: gilmarbarreto2@gmail.com.
J.C.A. Cintra, PhD, Full Professor, Escola de Engenharia de São Carlos, Universidade de São Paulo, 13.560-970 São Carlos, SP, Brazil. e-mail: cintrajc@sc.usp.br.
N. Aoki, PhD, Assistent Professor, Escola de Engenharia de São Carlos, Universidade de São Paulo, 13.560-970 São Carlos, SP, Brazil. e-mail: nelson.aoki@uol.com.br.
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2. Material and Methods

2.1. Conception

The idea is to measure the average vertical displacement of a blow, from 15 blows of a hammer of 65 kg mass in a free fall height of 0.75 m over a two-part brass bushing pressed against a cylindrical steel rod. The bushing is connected to the rod by eight bolts with a tightening torque of 30 Nm. One reason for the choice of torque 30 Nm is that the authors wish the displacements of the bush, in a blow, to be such that match Nspt values in the range of 30 to 50 blows. On the other hand, the 30 Nm torque is located in the central range of variation of the torquemeter (5 to 50 Nm), which is interesting from the standpoint of accuracy. The relationship between the average displacement obtained by using standard equipment NBR 6484:2001 and that obtained using the alternative equipment corresponds to the average efficiency of the alternative equipment to the standard one. This procedure will allow the alternative equipment to be used in SPT by applying the correction coefficient obtained in the test.

2.2. Device

The device is composed of a steel base which supports a damping system comprised of four pads of neoprene with hardness shore A in the 88 to 92 range (Fig. 1). This neoprene hardness, besides having good properties related to: flexibility, mechanical strength, impermeability, durability, resistance to sunlight exposure and high temperature, has a higher impact resistance compared to a lower hardness neoprene.

A rod is mounted on the plate (Fig. 2) and a bronze bipartite bushing (Fig. 3) is fixed to a support (Fig. 4). The tightening of the bush against the cylindrical surface of the stem is provided by eight screws (Fig. 5) whose torque is controlled by an analogical torque wrench (Fig. 6). Figure 7 shows the device assembled and with the anvil used in the drilling equipment mounted on the truck.

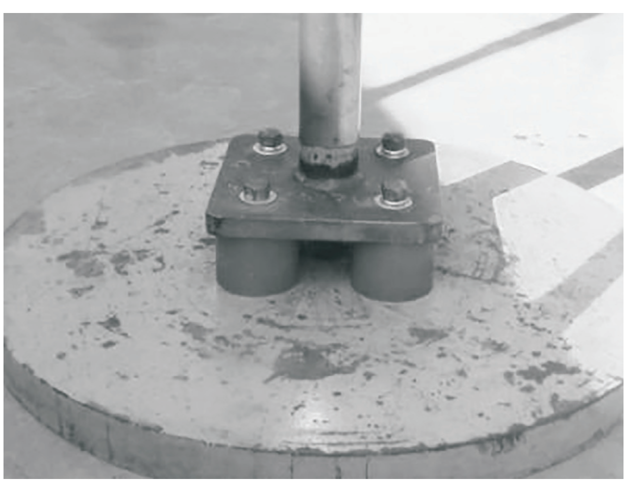

Figure 1 - Base and damping plate.

Figures 8 to 15 show the designs of the main parts of the device.

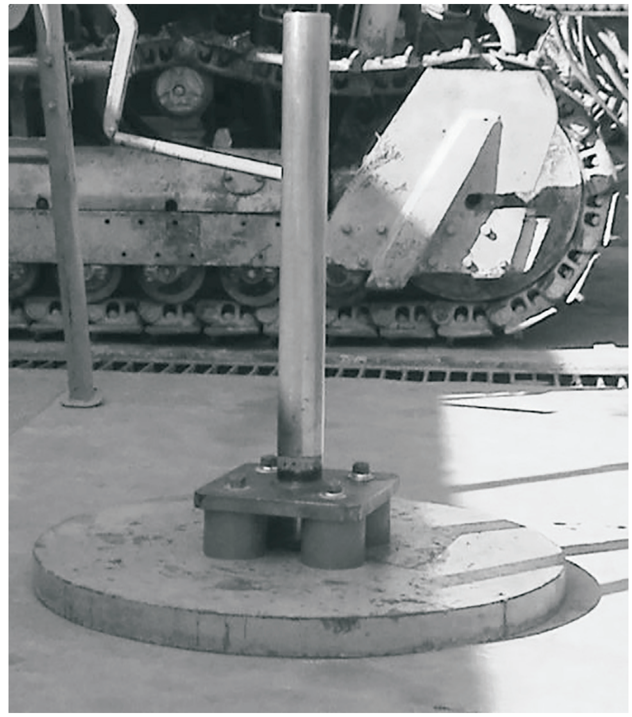

Figure 2 - Stem threaded in the damping plate.

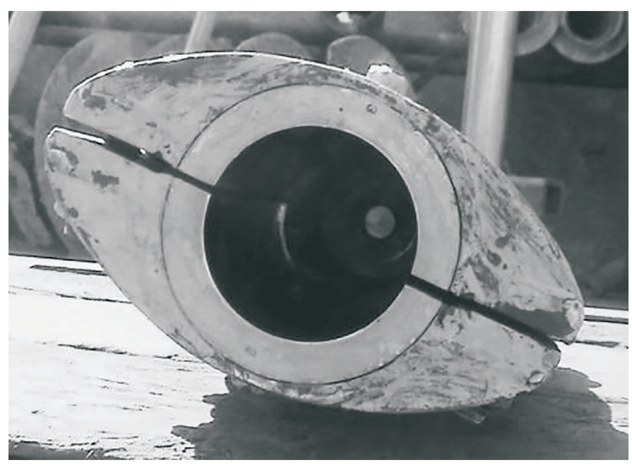

Figure 3 - Bushing mounted on the support.

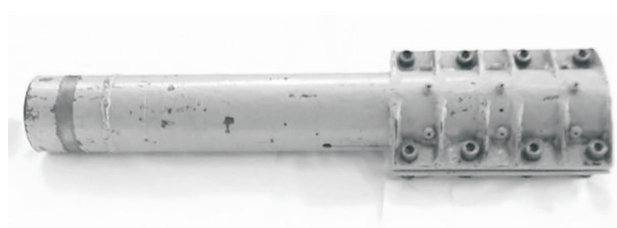

Figure 4 - Support.

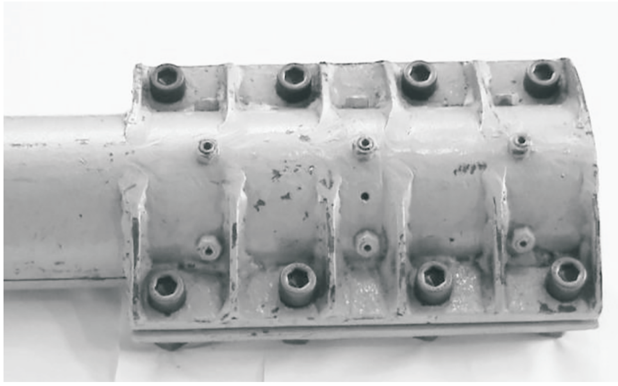

Figure 5 - Detail of the tightening bolts.

Figure 6 - Torquemeter.

Figure 7 - Device mounted.

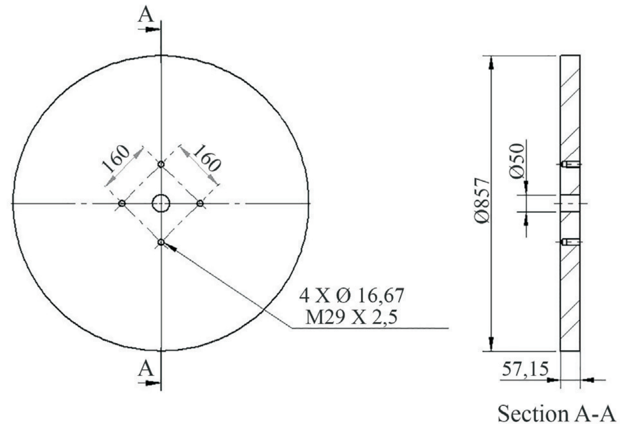

Figure 8 - Base.

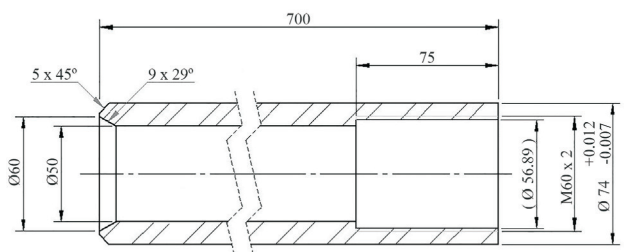

Figure 9 - Stem.

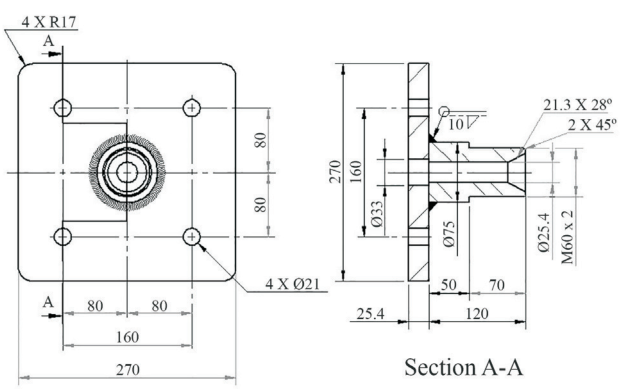

Figure 10 - Damping plate.

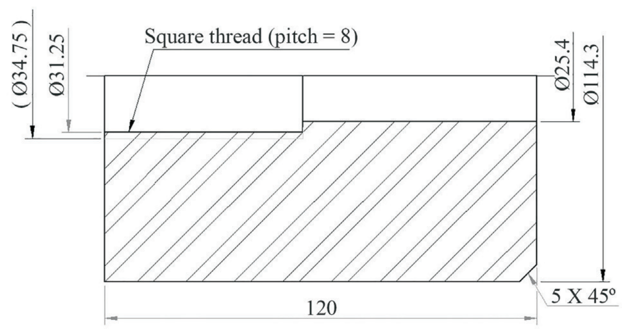

Figure 11 - Threaded bushing.

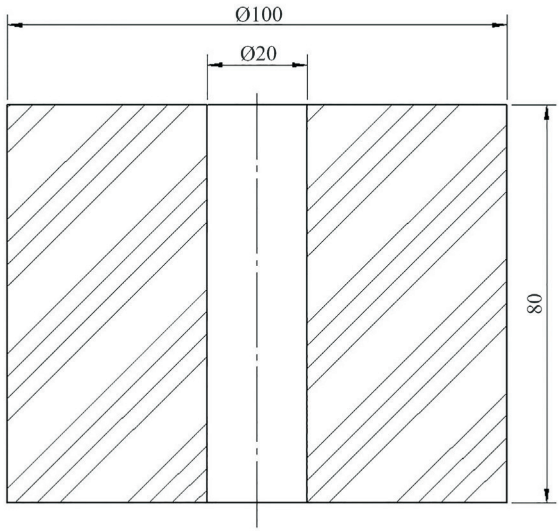

Figure 12 - Neoprene damper.

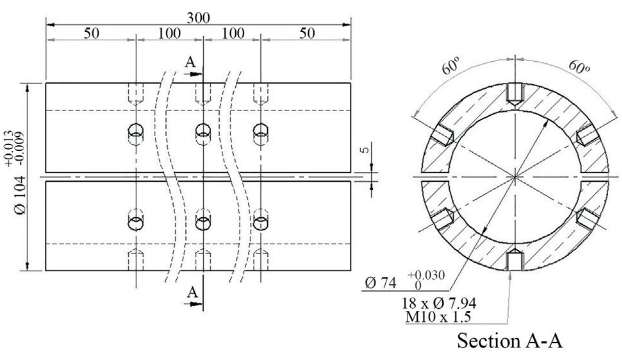

Figure 13 - Bushing.

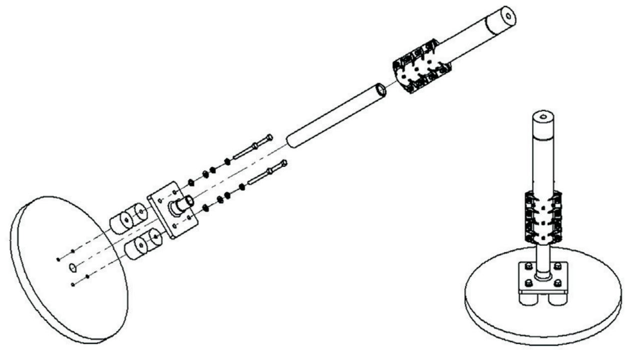

Figure 15 - Assembling of the device.

2.3. Instruments and procedures

An analog torquemeter with readings from 5-50 Nm to 0.50 Nm precision (Fig. 16) and a 1 mm precision steel scale (Fig. 17) were used in the dynamic tests. A hydraulic unit, a hydraulic cylinder, an analog manometer for measurements from 0 to 7000 kPa with 100 kPa precision and six extensometers with readings of 0-50 mm and 0.01 mm precision were used in the static tests. Although the steel scale used in the tests (ED-1 to ED-4) has a precision of 1 mm, it could be used without restriction as the mean displacement of the hammer that was obtained by dividing the accumulated displacement of the bushing by the number of hammer blows, resulting in a small error. On the other hand, the uncertainty associated with the reading of the scale and with the need to interpolate between scale markings is relatively easy to estimate. So, considering the millimeter markings on a ruler scale, it is reasonable to say that

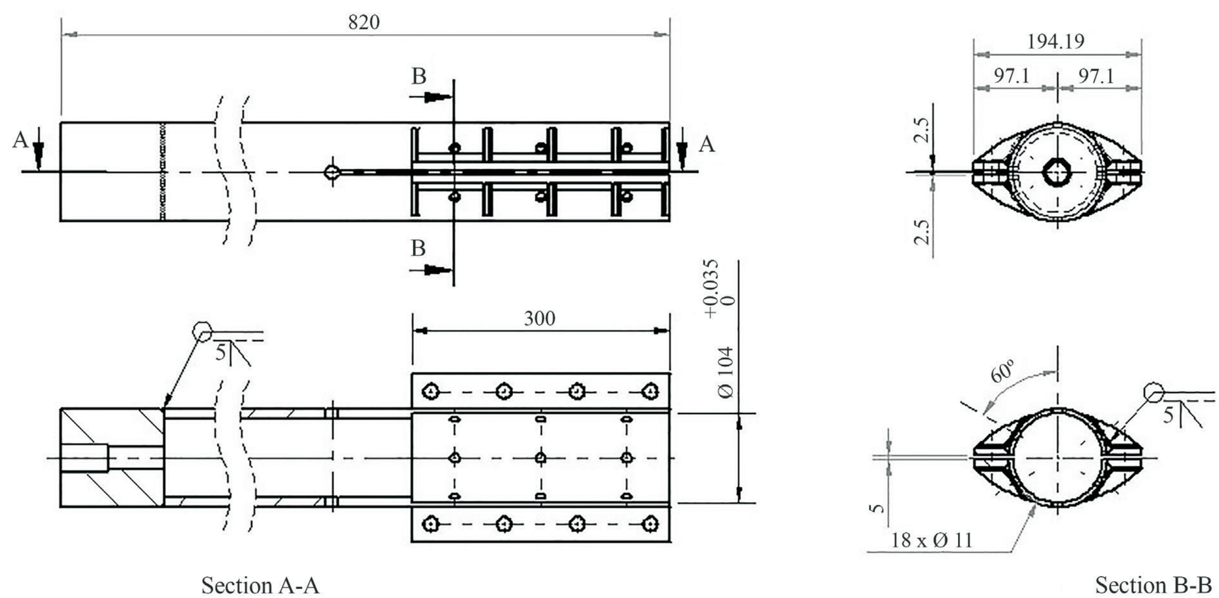

Figure 14 - Support of the bushing.

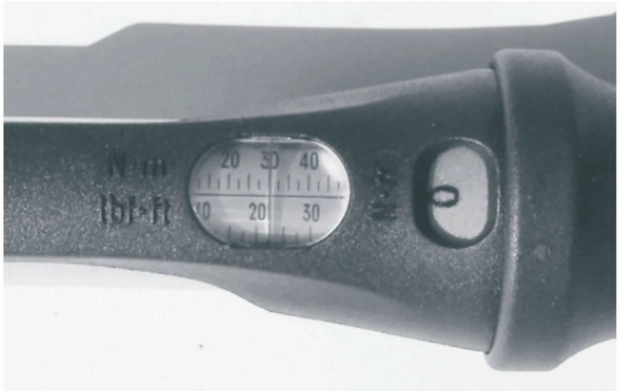

Figure 16 - Analog Torquemeter with 0.50 Nm.

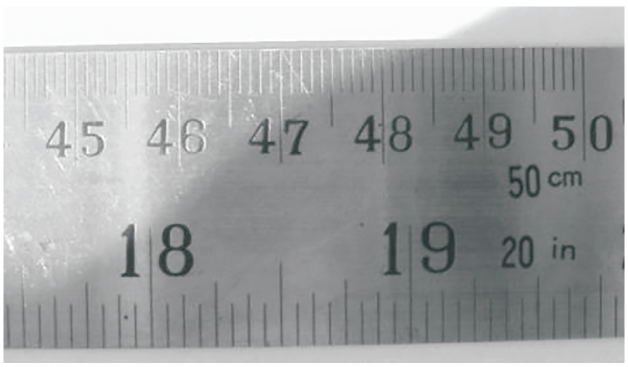

Figure 17 - Steel scale with 1 mm precision. precision.

the length could be read to the nearest millimeter at best. Therefore, a reasonable estimate of the uncertainty in this case would be $\delta_l = \pm 0.5$ mm which is half of the smallest division.

A more precise instrument for the measurement of displacement was not used since one of the goals of this experiment was to opt for simple thinks that work quite well.

The procedures to be followed for the testing are shown below.

a. The base was backed and kept in an undeformable, flat and horizontal place during all the tests to maintain the rigidity of the system and the vertical position of the rod, since the process is based on the comparison of displacements of the bushing relative to the shaft.

b. The rod was mounted on the base so that there was no gap between the threads (base and rod).

c. The bushing was mounted so that the space between its lower face and the upper face of the damping was 400 mm. A 25 mm diameter shaft was used as a template (Fig. 18).

d. The screws were numbered from left to right and from top to bottom and tightened as follows:

d1) Screws seven and eight were tightened with the template in the correct position.

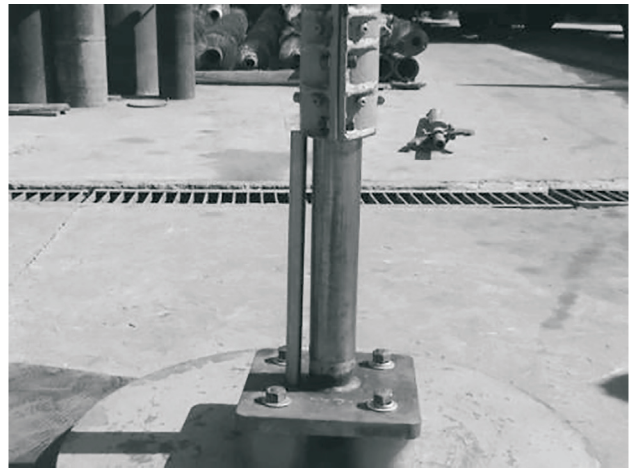

Figure 18 - Template positioned in the device.

d2) The template was removed from the device and screws 1 to 6 were tightened.

d3) The tightening torque of all screws was checked in the 1 to 8 order.

e. The anvil, corresponding to the tested equipment, was positioned in such a way that there was no gap between the male and female threads.

f. The test apparatus was placed so that the shaft was concentric with the hammer.

g. The hammer was lifted to a 75 cm height and then the first blow was given.

h. The distance from the lower face of the bushing to the upper face of the damping plate was measured.

i. Screws 1 and 2 were released and tightened with the adopted torque.

j. Screws 7 and 8 were released and tightened with the adopted torque.

k. Screws 1 to 6 were released and tightened with the adopted torque.

l. The tightening torque of screws 1 to 8 was checked.

m. The hammer was lifted to a height of 75 cm and then the second blow was given.

n. The procedures in items “i” to “m” were repeated until the fifteenth blow.

3. Results

Four experiments were performed and for each test 15 blows with a mass of 65 kg in free fall of 75 cm height were given. For each blow the displacement of the bushing relative to the rod fixed to the base was measured. The ED-1 test was performed using the manual lifting of the hammer by two men, with the tripod, pulleys, rope, hammer and other accessories in accordance with NBR 6484:2001. The test was conducted with a strict control of the standardized drop height of the hammer. Before each blow, the hammer was sustained for several seconds at a height 75 cm and then allowed to fall freely. The second test (ED-2) was conducted using a tripod equipped with a Borros Standard Penetration Test automatic trip hammer (Fig. 19).

The third test (ED-3) was carried out with the equipment mounted on a truck and equipped with an automatic hammer similar to CME - Central Mine Equipment Company (Fig. 20). The ED-4 test was performed with a tripod standardized by NBR 6484:2001; the hammer was lifted by two men, but with no strict control of the fall height. This procedure deliberately simulated a common practice.

Table 1 shows the results of the tests and Table 2 shows the various values calculated from the results.

The correction factor (*Cf*) based on the energy transferred from the hammer to the rod can be expressed by

$$Cf = \frac{\delta_{mTEST}}{\delta_{mSTANDARD}} \quad (1)$$

where δ_{mTEST} is the average displacement in the test and $\delta_{mSTANDARD}$ is the average displacement test standardized by ABNT.

Therefore N-value must be corrected by the correction factor for the efficiency of the standard equipment as shown below:

$$N_{STANDARD} = Cf.N_{TEST} \quad (2)$$

where $N_{STANDARD}$ is the N-value corrected for the standard efficiency and N_{TEST} is the N-value obtained in the test.

A static test (EE-1) with screw tightening torques of 10 Nm, 15, 20, 25 and 30 Nm was performed to determine the loads of slip, simulating a static load test in the standard sampler (Aoki *et al.*, 2007) and two static tests (EE-2 and EE-3) with tightening torque of 30 Nm were conducted to obtain the load-displacement curve of the bushing. Figure 21 shows the assembling of the test and Fig. 22 shows the results.

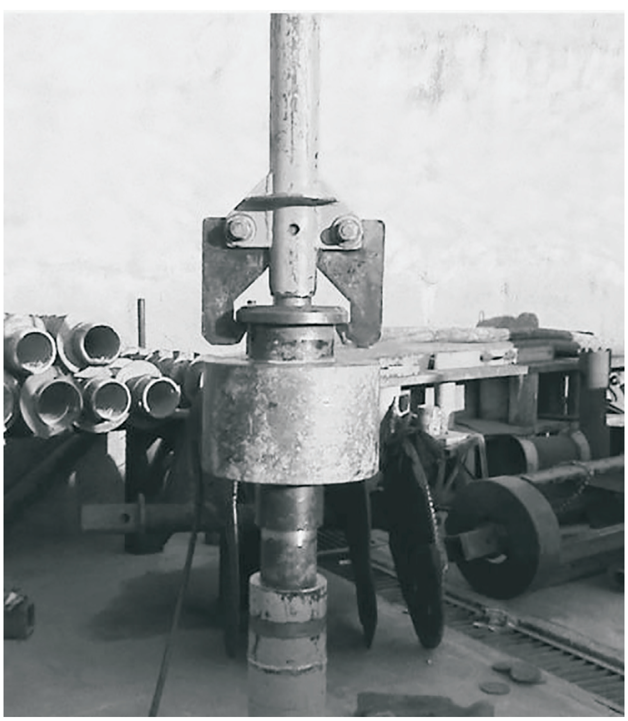

Figure 19 - Borros SPT automatic hammer.

Figure 20 - Equipment mounted on a truck.

Whereas the displacement of the bushing relative to the rod just before reaching the friction load between two parts is too small, a simplified load-settlement curve was adopted (Fig. 23) for the torque tightening of 30 Nm on the screws. This simplification facilitates the determination of the efficiency of the SPT test system.

The efficiency of the SPT test system can be expressed by

$$\eta = \frac{W}{U} \quad (3)$$

where η is the average efficiency of the SPT test system, *W* is the work done by force "*F*" necessary to slip the bushing and *U* is the standard potential energy - approximately 478.1 J - of the SPT.

The work done by force (*F*) is approximately equal to the area under the load-settlement curve, as Aoki, *et al.* (2007).

Table 3 shows the transfer efficiencies on the basis of the work done by force "*F*" and the relationship between efficiency and relative efficiency for each SPT test system for a tightening torque of 30 Nm using equation F = 1.3714 T.

Two load tests (EE-2 and EE-3) were performed using a comparing device of SPT to validate the simplified load-settlement curve. The loading and unloading phases were separated, respectively, into 13 and 7 stages. For both tests the tightening torque of the screws that creates the radial tensions in the rod was 30 Nm and the displacements of the bushing and the damping plate were measured at times t = 0 min and t = 5 min. using four dial gages with 0.01 mm accuracy and 50 mm displacement.

Table 1 - Displacement of the bushing (mm).

Number of the blow	Li_{ED1}	δ_{ED1}	Li_{ED2}	δ_{ED2}	Li_{ED3}	δ_{ED3}	Li_{ED4}	δ_{ED4}
1	392	8	393	7	391	9	392	8
2	384	8	386	7	381	10	386	6
3	375	9	378	8	372	9	381	5
4	368	7	371	7	363	9	373	8
5	360	8	364	7	353	10	366	7
6	353	7	357	7	344	9	360	6
7	346	7	350	7	335	9	353	7
8	339	7	344	6	326	9	347	6
9	331	8	337	7	317	9	341	6
10	324	7	331	6	308	9	335	6
11	317	7	324	7	299	9	329	6
12	310	7	317	7	290	9	323	6
13	303	7	310	7	282	8	319	4
14	295	8	303	7	273	9	313	6
15	287	8	296	7	264	9	307	6
δt	***	113	***	104	***	136	***	93
δm	***	7.5	***	6.9	***	9.1	***	6.2

Li_{ED1} - reading on the scale for ED-1 test; Li_{ED2} - reading on the scale for ED-2 test; Li_{ED3} - reading on the scale for ED-3 test; Li_{ED4}reading on the scale for ED-4 test.

δ_{ED1} - displacement for test ED-1; δ_{ED2} - displacement for test ED-2; δ_{ED3} - displacement for test ED-3; δ_{ED4} - displacement for test ED-4.

δt - total displacement; δm - mean displacement.

Table 2 - Values calculated based on the test results.

Test	Total displacement (δ_t) (mm)	Average displacement (δ_m) (mm)	Average standard deviation (sd) (mm)	Coef. of variation (%)	Relative efficiency (ηr)(%)	Factor of efficiency
ED-1	113	7.5	0.6	8.0	100	1.00
ED-2	104	6.9	0.5	7.2	92	0.92
ED-3	136	9.1	0.5	5.5	120	1.20
ED-4	93	6.2	1.0	16.1	82	0.82

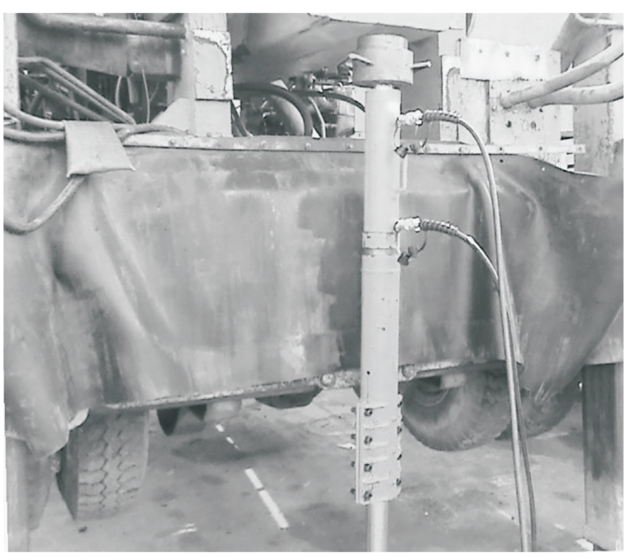

Figure 21 - Assembling of the static test.

In the EE-2 test two dial gages, numbered 1 and 2, were used. The magnetic bases were fixed on the base of the device and the contact tips were lightly pressed against the lower face of the bushing. Four gages numbered 3 to 6 were also used; their magnetic bases were fixed on the base

Table 3 - Efficiency of SPT test system.

Test	δ_m (mm)	F (N)	W (J)	η (%)	η/η_r
ED-1	7.5	41142	310	65	0.65
ED-2	6.9	41142	285	60	0.65
ED-3	9.1	41142	373	78	0.65
ED-4	6.2	41142	255	53	0.65

d_m is the average displacement; *F* is the load slip bronze bushing; *W* is the work done by force "*F*"; η is the transfer efficiency of the SPT tested system; η_r is the relative transfer efficiency of the standard SPT test system = 100%.

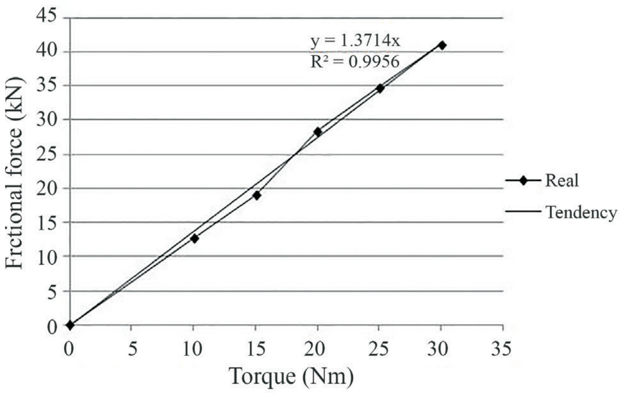

Figure 22 - Load slip bronze bushing (EE-1).

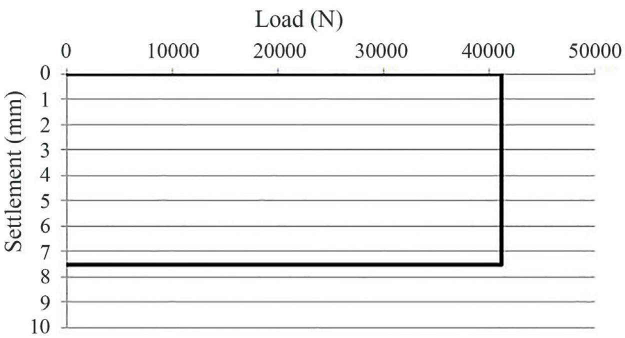

Figure 23 - Simplified load-settlement curve.

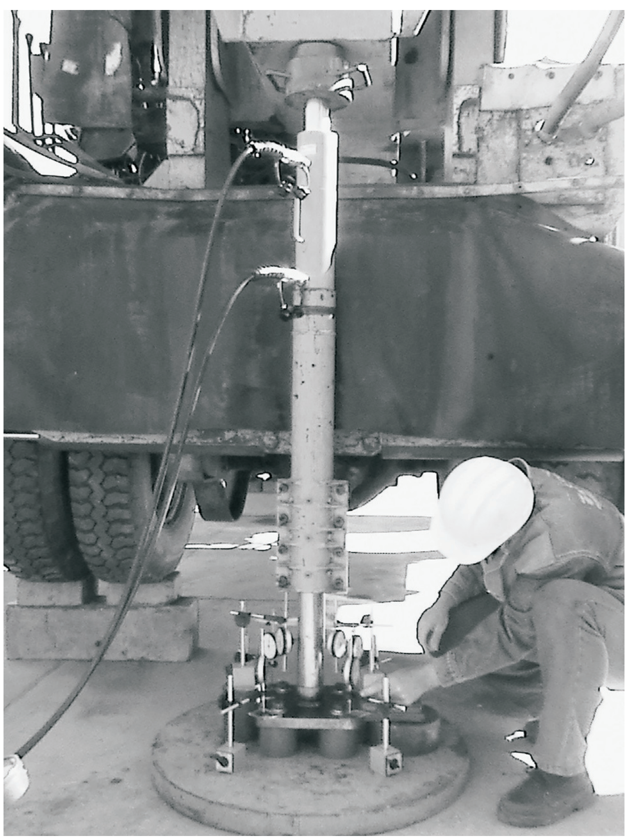

Figure 24 - Mounting of the load test.

of the device and the contact tips were lightly pressed against the upper face of the damping plate. Figure 24 shows the assembly of this test and Fig. 25 shows the assembling of the dial gages. A drill rig weighing approximately 170 kN was used as the reaction system.

To draw the load-settlement curve of the bushing, the loads were obtained multiplying the pressure by the cross-sectional area of the hydraulic jack and the displacements were obtained by the difference between the means of the displacements of extensometers 1 and 2, and 3 to 6.

This procedure was necessary because the area under the load-settlement curve of the bushing must represent the work done by the non-conservative forces, since the displacements of extensometers 1 and 2 are already embedded in the displacements relative to the base of the damper plate.

Figure 26 shows the load-settlement curve of the bushing. The area under this curve represents the work done by the non-conservative forces, *i.e.* 292.1 J considering the upper limit of 7.5 mm (ED-1). The work was obtained by the trapezoid method integration, for displacement values from 0 to 7.5 mm, *i.e.*:

$$W(x) = \int^{x} N(x)d(x) \quad (4)$$

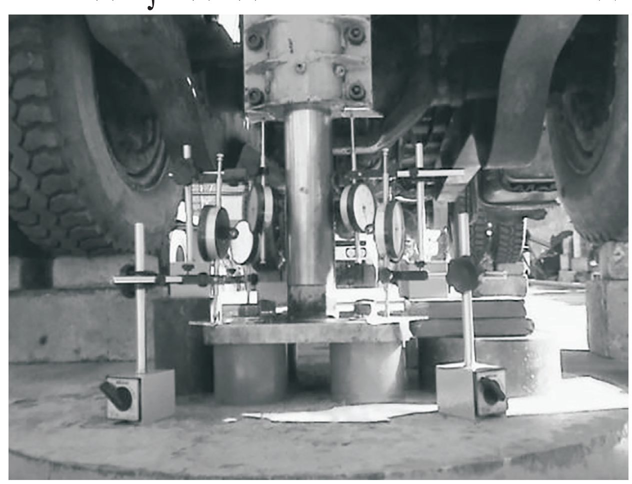

Figure 25 - Mounting of the dial gages.

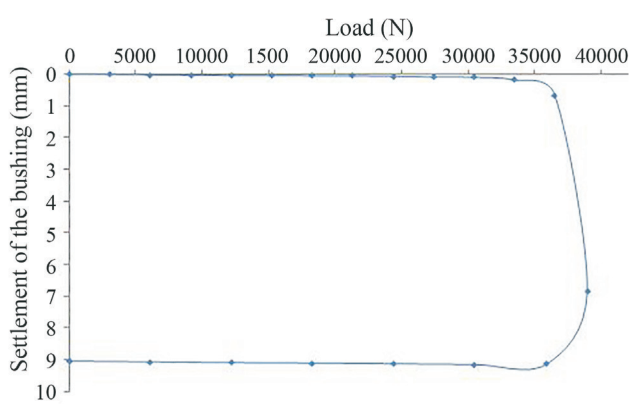

Figure 26 - Load-settlement curve (EE-2).

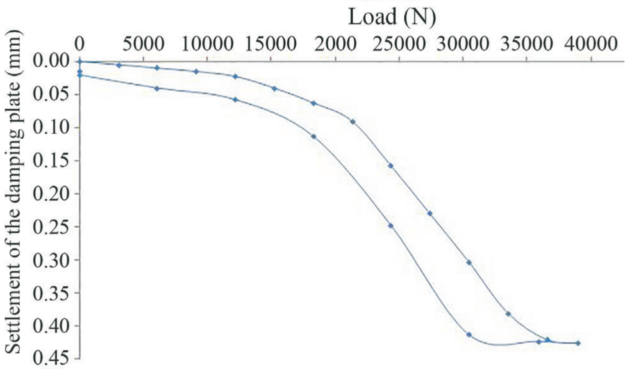

Figure 27 - Load-settlement curve of the damping plate (EE-2).

where *W(x)* is the work done by non-conservative forces and/or conservative forces and *N(x)* is the potential energy normalized (478.1 J) in the SPT.

Figure 27 shows the load-settlement curve of the damping plate. The area under the curve represents the work done by the conservative forces, whereas for the displacement of 7.5 mm of the bushing obtained in the dynamic test, the work done was 10.8 J.

The efficiency of the dynamic test (ED-1) can be calculated as the ratio between the total work done and the potential normalized energy of the SPT. Therefore,

$$\eta = \frac{Wt}{U} = \frac{292.1}{478.1} \times 100 = 61.1\% \quad (5)$$

where *Wt* is the work done by non-conservative forces and *U* is the standard potential energy - approximately 478.1 J - of the SPT.

The variation in the efficiency obtained by the model instrumented with dial gages compared to that obtained by the simplified model can be calculated by the expression

$$\Delta\eta = \frac{\eta s - \eta i}{\eta i} = \frac{0.650 - 0.611}{0.611} \times 100 = 6.4\% \quad (6)$$

where ηs is the transfer efficiency of the SPT test system obtained by the simplified model and ηi is the transfer efficiency of the standard SPT test system obtained by the instrumented model.

In the EE-3 trial two dial gages, numbered 1 and 2 were used and their magnetic bases were fixed on the damping plate of the device and the contact tips were lightly pressed against the lower face of the bushing. The other procedures were identical to those for EE-2 test. Figure 28 shows the assembling of the test and Fig. 29 shows the assembling of the dial gages.

The area under the curve represents the work done by the conservative forces, whereas for the displacement of 7.5 mm of the bushing obtained in the dynamic test, the work done was 10.8 J.

The load-settlement curve of the bushing was obtained in the same manner as in the EE-2 test and settlements were obtained directly from the readings in the first and second dial gages since these displacements correspond to those caused by non-conservative forces.

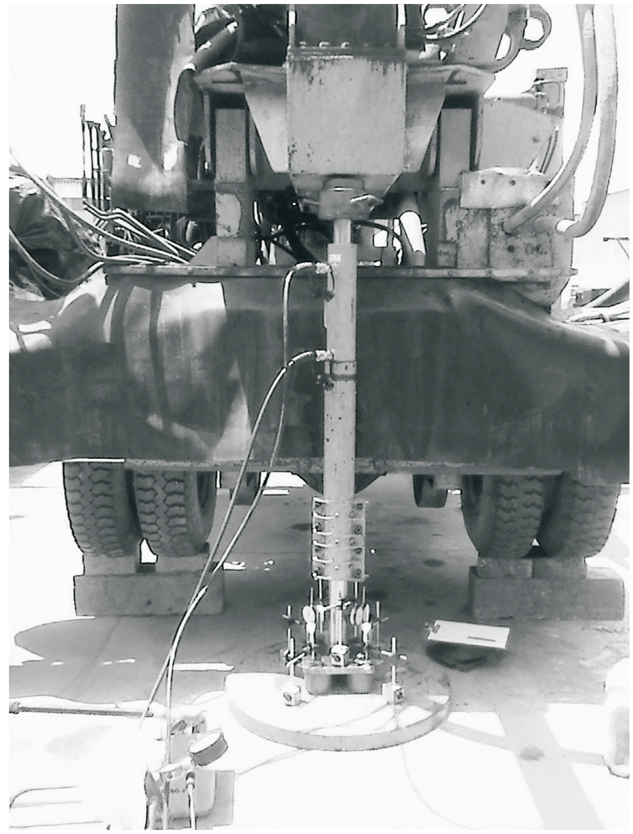

Figure 28 - Mounting of the load test.

Figure 30 shows the load-settlement curve of the bushing. The area under this curve, which represents the work done by non-conservative forces, resulted in 312.7 J, considering the settlement of 7.5 mm obtained in the dynamic test.

Figure 31 shows the load-settlement curve of the damping plate. The area under this curve represents the work done by the conservative forces, whereas for the settlement of 7.5 mm of the bushing obtained in the dynamic test, the work done was 9.3 J.

The efficiency of the dynamic test (ED-1) can be calculated as the ratio between the total work done and the potential normalized energy of the SPT. Therefore

$$\eta = \frac{Wt}{U} = \frac{312.7}{478.1} \times 100 = 65.4\% \quad (7)$$

The variation in the efficiency obtained by the model instrumented by dial gages in comparison to that obtained by the simplified model can be calculated by the expression:

$$\Delta\eta = \frac{|\eta s - \eta i|}{\eta i} = \frac{|0.650 - 0.654|}{0.654} \times 100 = 0.61\% \quad (8)$$

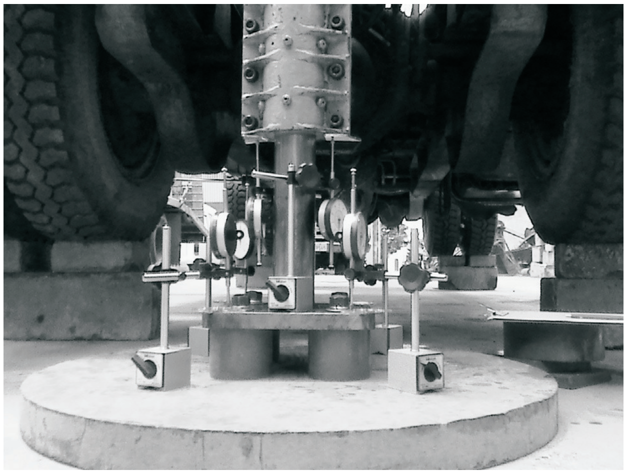

Figure 29 - Mounting of the dial gages (EE-3).

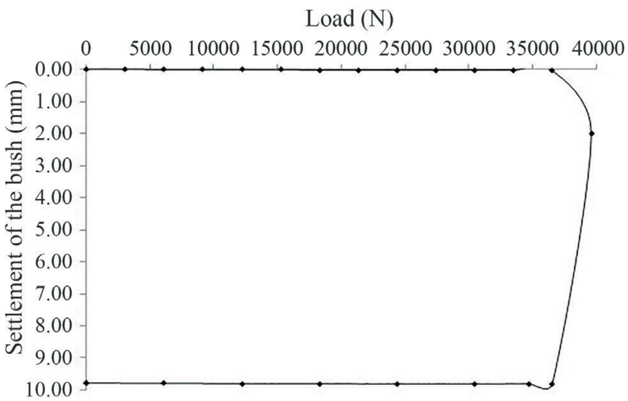

Figure 30 - Load-settlement curve of the bushing (EE-3).

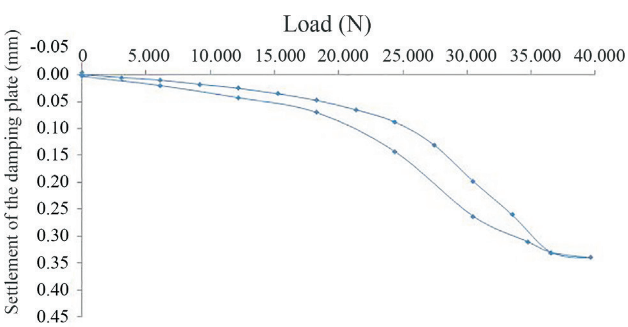

Figure 31 - Load-settlement curve of the damping plate. (EE-3).

The percentage change between the work done by the non-conservative forces, respectively, for tests EE-2 and EE-3 can be computed as

$$\Delta T = \frac{Wt_{EE-3} - Wt_{EE-2}}{Wt_{EE-2}} \times 100 = \frac{321.7 - 292.1}{292.1} \times 100 = 7.1\% \quad (9)$$

where Wt_{EE-2} is the work done by conservative forces for test EE-2 and Wt_{EE-3-} is the work done by conservative forces for test EE-3.

The load and unload curves of the damping plate were not coincident, probably due to the hysteresis effect.

4. Conclusions

The lowest coefficient of variation of the displacements was obtained for the dynamic test using mechanized equipment mounted on the truck with an automatic hammer, suggesting a tendency of repeatability of this test.

The highest coefficient of variation of displacements was obtained for the standard manual test, but without a strict control of the fall of the hammer, showing a significant influence of human factor on the results.

The low variability of displacements that occurred in the tests with mechanized equipment suggests a tendency of repeatability of these tests.

The energy obtained with the simplified load-settlement curve was consistent with the energy calculated based on the real load-displacement curve, indicating that it is possible to use the simplified model to obtain the transferred energy efficiency.

Considering the results of the tests and simplicity of construction and operation of the device, it can be used routinely by universities and companies to calibrate and compare the efficiencies of any SPT test system and the standard equipment by applying the necessary correction factor.

Other tests to measure the displacement can be performed with different tightening torques in the screws to verify if the values of the efficiencies will be repeated.

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