ABSTRACT

The aim of this paper is to show how to obtain the impact efficiency from a static load test performed on the standard penetration test (SPT) sampler. In a dynamic test, the maximum resisting force developed during the hammer impact depends on the displacement (static component), velocity (damping component) and acceleration (inertial component). At the instant corresponding to the dynamic test end, experimental data show that the elastic potential energy is negligible. As a consequence, the work done is almost equal to the potential energy stored in the system. Similarly, in a static load test performed on the sampler right after the dynamic test, the elastic potential energy is also negligible. As a consequence, the work done is almost equal to the potential energy stored in the system. Thus, in both tests, the maximum penetration of sampler into the soil is permanent. Additionally, it was verified that the potential energy stored in dynamic test is almost equal to the potential energy stored in static test, for the same value of sampler penetration. Thus, the efficiency can be obtained dividing the system potential energy by the SPT nominal potential energy (474 J).

Key words: dynamic load test, field test, in-situ test, standard penetration test, static load test (IGC: C3)

INTRODUCTION

The standard penetration test (SPT) is an in-situ test widely used in Brazil and in many other countries around the world. The evaluation of the energy arriving to the top section of the SPT sampler is traditionally done by means of sensors installed in the upper part of the rod. The first compression wave is integrated over the time required for the wave to reach the top of the sampler. In this approach, the efficiency increases with the increase in the rod length, as demonstrated by Schmertmann and Palacios (1979). However, it seems to be in disagreement with the common sense.

For this reason, Aoki and Cintra (2000) have redefined the SPT efficiency based on the potential energy curve corresponding to the top of the sampler. This energy is numerically equal to the kinetic energy which arrives to the top section of the SPT sampler. According to Hamilton’s Principle (Aoki, 1997), at the end of the hammer impact (after the system has been discharged), the potential energy is transformed into elastic potential energy and work done by the non conservative resisting forces. The work is numerically equal to the area enclosed by the loading and unloading branches of the resistance versus displacement curve at the top of the sampler. In addition, the SPT efficiency is represented by the work done during the sampler penetration, immediately after the impact, divided by the available potential energy before the impact. On the other hand, the work is equal to the product of the resisting force by the permanent displacement. As a consequence, since the work and the displacement are known, the resisting force developed during the sampler penetration can be derived.

According to Abou-Matar et al. (1996), in a dynamic test, the maximum resisting force developed during the impact of the standard hammer depends on the displacement (static component), velocity (damping component) and acceleration (inertial component). The potential energy stored in the system, at the instant corresponding to the maximum sampler penetration, can be obtained by monitoring the deformation and acceleration of the top section of the rod. At the instant corresponding to the dynamic test end, experimental data show that the elastic potential energy is negligible. As a consequence, the work done is almost equal to the potential energy stored in the system. Similarly, in a static load test performed on the sampler, right after the dynamic test, experimental data show that the elastic potential energy is also negligible. As a consequence, the work done is almost equal to the potential energy stored in the system. In both dynamic and static tests, the maximum penetration of sampler into the soil is permanent. Additionally, it was verified that the potential energy stored in dynamic test is almost equal to the potential energy stored in static test, for the same value of sampler penetration. Thus, the efficiency can be obtained dividing the system potential energy by the SPT nominal potential energy (474 J).

To verify these propositions, a series of standard
penetration tests was performed in a non-saturated sandy soil field, in Araras, Brazil. The readings of the N-value or N\text{SPT} index were complemented with readings of the kinetic energy. The measurement of the kinetic energy was performed with an SPT analyzer, through strain gauges and accelerometers installed at the top of the sampler. Immediately after the determination of the N\text{SPT} index, a static load test was performed applying an increasing static load on the string of rods and SPT sampler. The SPT apparatus was mounted on a truck, which was also used as the load reaction frame.

The dynamic and static load test analyses have shown that: a) in both cases, nearly all the system deformation energy was transformed into work done by the non-conservative resisting forces; b) the measured kinetic energy in the dynamic test is numerically the same as the deformation energy assessed by the area under the load-displacement curve corresponding to the static test; c) the magnitude of the sampler penetration resisting force, evaluated from the work measured in the dynamic test, is equal to the applied load magnitude in the static test, corresponding to the maximum displacement in the dynamic test.

From the above results, it has been concluded that: a) the work done by the system, assessed from the static load test on the sampler, allows the evaluation of the impact efficiency in standard penetration tests; b) for a specific depth, it is possible to convert the N\text{SPT} index into a resisting force to the sampler penetration.

**SPT EFFICIENCY MEASUREMENTS**

*The Traditional Definition of the SPT Efficiency*

Figure 1 shows a schematic diagram to help understand the definition of the SPT efficiency. The hammer, weighing 624 N, falls from a height \( h_0 \) of 0.76 m, hits the anvil located at the top of the system consisting of rods (with total length \( \ell \)), a sampler (with length \( b \)) and the soil (ASTM D1586–99). The origin O of the system of reference is located at the anvil. The section A is located at the top of the sampler.

The kinetic energy corresponding to the first compression wave measured at the top of the rods (section O), is defined as:

\[
T_z = \int_0^{t_z} F(0, t) \times v(0, t) \times dt
\]  

(1)

where \( T_z \) is the kinetic energy corresponding to the first compression wave, \( F(0, t) \) is the normal force at section O, \( v(0, t) \) is the velocity of the compression wave at section O and \( t_z \) is the elapsed time for the first compression wave to reach section A.

Usually, the impact efficiency (\( \eta \)) is defined as (Schmertmann and Palacios, 1979 and ASTM D4633–86):

\[
\eta = \frac{T_z}{T^*} \times 100(\%)
\]  

(2)

where \( T_z \) is the energy corresponding to the initial compression wave entering the sampler and \( T^* \) is the potential hammer energy (474 J).

*The Redefinition of the SPT Efficiency*

The maximum energy \( T_0 \) applied at the top of the system comprising the anvil, rods, sampler and soil is given by (Aggour and Radding, 2001):

\[
T_0 = \int_0^{\infty} F(0, t) \times v(0, t) \times dt
\]  

(3)

The maximum energy transferred to the top of the arrangement sampler-soil is given by:

\[
T_A = \int_{t_D}^{\infty} F(\ell, t) \times v(\ell, t) \times dt
\]  

(4)

where \( F(\ell, t) \) is the normal force at section A, \( v(\ell, t) \) is the velocity at section A and \( t_D \) is the elapsed time for the compression wave to reach section A.

The maximum values of the kinetic energy at sections O and A are \( T_0 \) and \( T_A \), respectively (Fig. 2). They correspond to particular solutions of the energy wave equation for these sections.

Since the deformations on the sampler-soil system, located below point A, are caused by the kinetic energy given by Eq. (4), Aoki and Cintra (2000) suggested a new definition for the SPT efficiency based on this energy:

\[
\eta^* = \frac{T_A}{T^*} \times 100(\%)
\]  

(5)
where $\eta^*$ is the efficiency measured at section A, $T_A$ is the maximum energy transferred to the sampler-soil system and $T^*$ is the SPT standardized potential energy (474 J).

**MEASUREMENT OF THE RESISTING FORCE IN THE SPT**

**Hamilton’s Principle**

Hamilton’s Principle variational equation (Clough and Penzien, 1993) is given by:

$$\int_{t_1}^{t_2} \delta(T - V)dt + \int_{t_1}^{t_2} \delta(W_{nc})dt = 0 \quad (6)$$

where $\delta$ is the variation during the time interval $(t_2- t_1)$, $T$ is the kinetic energy in the system, $V$ is the potential energy in the system and $W_{nc}$ is the work done by non-conservative forces, including the damping forces. Almost all traditional dynamic formulas for pile driving are based on Hamilton’s Principle, which is better known as the energy conservation principle.

An application of Hamilton’s Principle to the SPT Sampler Penetration

Figure 3 shows the loading and unloading curves, corresponding to the sampler penetration into the soil. The stretches $OA$ and $OB$ correspond to the loading paths in the dynamic and static tests, respectively. The stretches $AC$ and $BC$ correspond to the unloading paths in the dynamic and static tests, respectively. In this figure, $Q_S$ and $R_T$ represent the maximum resisting forces in the static and dynamic tests, respectively. In the same figure, $K$ and $S$ represent the elastic and the permanent components of the maximum penetration ($DMX$), respectively.

At instant $t_1$ the compression wave reaches the top of the sampler and at instant $t_2$ the sampler penetration into the soil reaches its maximum value ($DMX$). At instant $t_2$, the potential energy, denoted by $V_A$, is numerically equal to area $OAD$. The instant $t_3$ corresponds to the end of the impact, when the permanent penetration equals to $S$ and the elastic rebound equals to $K$.

Table 1 shows the variations of the kinetic energy ($T$), potential energy ($V$) and the non-conservative work done ($W_{nc}$), at the top of the sampler, during the time interval $(t_2- t_1)$, according to Hamilton’s Principle.

Hence, at the instant $t_2$ when the sampler penetration reaches its maximum value ($DMX$):

$$V_A = T_A \quad (7)$$

Applying Hamilton’s Principle (Eq. (6)) to the time interval $(t_2- t_3)$, the following equation can be written:

$$0 + V_e - V_A + W_A = 0 \quad (8)$$

Hence, at the end of the impact, when the sampler permanent penetration is equal to $S$:

$$V_A = V_e + W_A \quad (9)$$

As a matter of fact, Figs. 3 and 4 show that the total area $V_A$ equals to the sum of the area $V_e$ (elastic deformation potential energy) plus the area $W_A$ (work done by the non-conservative resisting force $R$, during the time interval $(t_2- t_3)$). The same reasoning can be applied for the static load test.

**Resisting Force Developed during the Sampler Penetration**

The deformation energy $V_A$ is evaluated from the velocity ($v$) versus time and force ($F$) versus time graphs provided by the sensors installed at the top of the SPT.

![Fig. 3. SPT sampler loading and unloading curves](image)

![Fig. 4. SPT apparatus used for performing the dynamic (a) and the static load (b) tests](image)

**Table 1. Variation of the energy during the elapsed times ($t_2-t_1$) and ($t_3-t_2$)**

<table>
<thead>
<tr>
<th>Time</th>
<th>$T$</th>
<th>$V$</th>
<th>$W_{nc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1$</td>
<td>$T_A$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$t_2$</td>
<td>0</td>
<td>$V_A$</td>
<td>0</td>
</tr>
<tr>
<td>$t_3$</td>
<td>0</td>
<td>$V_e$</td>
<td>$W_A$</td>
</tr>
<tr>
<td>variation $\delta_{12}$</td>
<td>($-T_A$)</td>
<td>($V_A$)</td>
<td>(0)</td>
</tr>
<tr>
<td>variation $\delta_{23}$</td>
<td>0</td>
<td>($V_e-V_A$)</td>
<td>($W_A$)</td>
</tr>
</tbody>
</table>
sampler:

\[ V_A = \int_0^\infty F(\xi, t) \times v(\xi, t) \times dt \] (10)

With the exception of resilient soils, the elastic rebound \( K \) is very small when compared with the sampler permanent penetration (S). Hence, Eq. (10) can be rewritten as:

\[ V_A = W_A \] (11)

However, the work is equal to the product of the resisting force by the permanent penetration:

\[ W_A = R_T \times S \] (12)

where \( R_T \) is the resisting force at failure.

At the instant when the maximum displacement (DMX) occurs, the area comprised between the stretches \( OA \) and \( OB \) is very small, as it was verified by the experimental data. Thus, the only resisting force available is the static component:

\[ R_T = Q_S \] (13)

It can be concluded that for any hammer impact on the SPT sampler, the static resisting force, as previously defined, can be evaluated by the following equation:

\[ R_s = \frac{W_A - V_A}{S} = \frac{V_A - T_A}{S} \] (14)

On the other hand, when driving the SPT sampler to obtain the \( N_{SPT} \) index, the penetration \( S \) per blow varies. The penetration mean value \( S_m \) can be evaluated by the following equation:

\[ S_m = \frac{0.3}{N_{SPT}} \times N_{SPT} \] (15)

In this case, the static penetration resistance corresponding to the \( N_{SPT} \) index is given by:

\[ R_s = T_A \times \frac{N_{SPT}}{0.3} \] (16)

Combining Eq. (16) with Eq. (5), it results:

\[ R_s = \frac{0.474 \times \eta^* \times N_{SPT}}{30} \] (17)

The \( N_{SPT} \) resistance index can be transformed into an equivalent static resisting force by means of Eq. (17), if the average efficiency expressed by Eq. (5) is known. Therefore, the \( N_{SPT} \) resistance index can be considered as a parameter with a specific physical meaning. Finally, considering Eqs. (5), (7) and (11), it can be shown that:

\[ \eta^* = \frac{W_A}{T_A} \times 100(\%) \] (18)

This equation shows that the efficiency measured at the top of the sampler section can be evaluated from the work done by the non-conservative resisting forces.

**EQUIPMENTS AND PROCEDURES**

To verify these propositions, a series of standard penetration tests was performed in a non-saturated sandy soil field, in Araras, Brazil (Neves, 2004). The readings of the \( N \)-value or \( N_{SPT} \) index were complemented with readings of the kinetic energy.

Immediately after the determination of the \( N_{SPT} \) index, a static load test was performed applying an increasing static load on the rods-SPT sampler setup. In this research, the SPT truck was used as the reaction frame. Figure 4 shows schematically the SPT apparatus used to perform the dynamic and the static load tests.

**Dynamic Test**

The dynamic tests were performed using an SPT apparatus equipped with an automatic hammer weighing 624 N, which falls from a height of 0.76 m, allowing a quick repetition of blows. The hammer hits a steel anvil with a mass of 6.28 kg. The kinetic energy was measured by means of an instrumented AW rod installed immediately above the sampler. For this reason, it is possible to measure the kinetic energy \( T_a \), which reaches the sampler and is transformed into deformation energy during the sampler penetration into the soil. The instrumented rod has two strain gauges and two piezoelectric accelerometers installed on it. The data were recorded by an SPT analyzer.

**Static Load Test**

The static tests were performed right after the last dynamic sampler penetration. The static loads were applied on the rod-sampler-soil system using a manual hydraulic jack. The loads were measured by a load cell with a reading accuracy of 0.1 kN. The displacements were measured by two extensometers installed on the rod in diametrical positions, fastened by means of magnetic fasteners.

After assembling the equipment, an initial load was applied to the system composed of rods, sampler, soil and reaction frame. After that, the corresponding initial displacement was shifted to zero. Before starting the static load test with the SPT sampler, the static resistance \( R_s \) was assessed by means of Eq. (16).

The load was increased in variable increments until its magnitude reached 2/3 of \( R_s \). Subsequently, all the load increments were constant and equal to 0.1 kN, which corresponds to the accuracy of the load cell used in the test. For each load step, displacement readings were recorded every minute, until the difference between two consecutive readings was less than 0.5 mm. Then, the next load step was applied. The adopted stabilization criterion was given by:

\[ (\rho_s, n - \rho_s, n-1) \leq 0.5 \text{ mm} \] (19)

where \( \rho_s, n \) is the reading at step \( n \) and \( \rho_s, n-1 \) is the reading at step \( n-1 \).

The deformation energy magnitude was estimated from the load-settlement curve obtained from the static load tests. This was accomplished through the performance of static load tests so that at least one sampler settlement was equal to the dynamic penetration magnitude
Table 2. SPT boring log

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>N_{SP}</th>
<th>Soil Classification</th>
<th>Depth (m)</th>
<th>N_{SP}</th>
<th>Soil Classification</th>
<th>Depth (m)</th>
<th>N_{SP}</th>
<th>Soil Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0/45</td>
<td></td>
<td>1</td>
<td>2/40</td>
<td></td>
<td>1</td>
<td>2/29</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1/14</td>
<td></td>
<td>2</td>
<td>1/36</td>
<td></td>
<td>2</td>
<td>2/36</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3/32</td>
<td>Slightly clayey fine sand:</td>
<td>3</td>
<td>3/30</td>
<td></td>
<td>3</td>
<td>3/33</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5/30</td>
<td>loose to medium dense</td>
<td>4</td>
<td>4/28</td>
<td>Silty fine sand: loose to</td>
<td>4</td>
<td>4/38</td>
<td>Silty fine sand: loose to</td>
</tr>
<tr>
<td>5</td>
<td>6/31</td>
<td></td>
<td>5</td>
<td>4/32</td>
<td>medium dense</td>
<td>5</td>
<td>4/32</td>
<td>medium dense</td>
</tr>
<tr>
<td>6</td>
<td>7/27</td>
<td></td>
<td>6</td>
<td>6/29</td>
<td></td>
<td>6</td>
<td>6/32</td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td></td>
<td></td>
<td>7</td>
<td>7/31</td>
<td></td>
<td>7</td>
<td>6/28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.7</td>
<td>Bottom of boring: refusal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>14/30</td>
<td>Silty little clayey fine sand:</td>
<td></td>
<td>8</td>
<td>6/28</td>
<td>Sandy silt: medium dense to</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>20/15</td>
<td>medium dense to very dense</td>
<td></td>
<td>9</td>
<td>42/30</td>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>9</td>
<td>35/15</td>
<td></td>
<td></td>
<td>10</td>
<td>35/10</td>
<td></td>
<td></td>
<td>10.1</td>
</tr>
<tr>
<td>10.1</td>
<td></td>
<td>Bottom of boring: refusal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. SPT results

<table>
<thead>
<tr>
<th>Case</th>
<th>Site</th>
<th>Test ID</th>
<th>Depth (m)</th>
<th>Measured N_{SP}</th>
<th>Average Penetration (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Araras 1</td>
<td>SP 05</td>
<td>6.0</td>
<td>7/27</td>
<td>39</td>
</tr>
<tr>
<td>2</td>
<td>Araras 3</td>
<td>SP 02</td>
<td>4.0</td>
<td>4/28</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>Araras 4</td>
<td>SP 01</td>
<td>6.0</td>
<td>6/32</td>
<td>53</td>
</tr>
<tr>
<td>4</td>
<td>Araras 4</td>
<td>SP 01</td>
<td>7.0</td>
<td>6/28</td>
<td>47</td>
</tr>
<tr>
<td>5</td>
<td>Araras 4</td>
<td>SP 01</td>
<td>8.0</td>
<td>7/29</td>
<td>41</td>
</tr>
</tbody>
</table>

corresponding to the last impact of the hammer, when the N_{SP} index was obtained:

\[ \rho_{\text{est}} \approx \rho_{\text{din}} \] (20)

where \( \rho_{\text{est}} \) is the magnitude of the total static settlement and \( \rho_{\text{din}} \) is the magnitude of the dynamic penetration corresponding to the last impact of the hammer.

After the minimum specified displacement was reached, the system was unloaded in variable steps. Since the instrumented rod is not waterproof, all the tests were performed above the water table, in order to prevent electronics malfunction.

### TEST RESULTS: DATA ANALYSIS AND DISCUSSION

#### Standard Penetration Test results

Table 2 shows the standard penetration test results (SP 05, SP 02 and SP 01). The \( N_{SP} \) indexes have been evaluated at every meter of depth at the test sites. Table 3 shows the average sample penetration per impact for some selected depths.

#### Dynamic Test Results

Figure 5 shows some selected force versus velocity graphs recorded by the SPT analyzer, during the last impact for determination of the \( N_{SP} \) index.

Table 4 shows the kinetic energy (\( T_A \)), the maximum force measured in the instrumented section (\( F_{\text{max}} \)) and the permanent sampler penetration into the soil (\( S \)). The kinetic energy corresponds to the last impact in each test, which is evaluated by means of Eq. (4). It should be noticed that this evaluation takes into account the integration from \( t_t \) to infinite, and not from zero to infinite, which would overestimate the energy magnitude.

The magnitude of the maximum forces measured is different for each case. The maximum magnitude force measured shows lower values and the subsequent force peaks are not noticeable. This fact explains, partially, the lower kinetic energy magnitudes for Cases 2 to 5. In these cases, no elastic recovery can be observed (\( K=0 \)) after each impact, meaning that the permanent penetration \( S \) is equal to the maximum displacement \( DMX \). This means that in the dynamic test almost all system deformation energy is transformed into work done by non-conservative resisting forces.

#### Static Test Results

Figure 6 shows the load-settlement curves corresponding to the static load tests. These curves show that the unloading stretches, starting from the maximum load applied, are nearly horizontal. This means that all deformation energy stored in the system up to this load level is transformed into work done by non-conservative resisting forces during the unloading phase. In this figure, it is also shown the point which represents the settlement equal to the permanent penetration corresponding to the last impact, shown in Table 4, and the corresponding load on the static test curve.

Table 5 shows the summarized results for the static load tests with maintained load, performed right after the last impact of a series of impacts for the \( N_{SP} \) index determination.

Table 5 shows the maximum loads and the corresponding settlements. Moreover, for each case, it shows...
Table 4. Dynamic test results

<table>
<thead>
<tr>
<th>Case</th>
<th>Kinetic Energy $T_A$ (J)</th>
<th>Maximum Force $F_{max}$ (kN)</th>
<th>Permanent Penetration $S$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>263</td>
<td>119</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
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<td>98</td>
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</tr>
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<td>4</td>
<td>146</td>
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<td>46</td>
</tr>
<tr>
<td>5</td>
<td>166</td>
<td>90</td>
<td>33</td>
</tr>
</tbody>
</table>

Fig. 5. Selected force versus velocity graphs recorded by the SPT analyzer

Fig. 6. Static load test

Fig. 7 shows a comparison between the kinetic energy $T_A$, measured during the dynamic test (Table 4) and the deformation energy $V_A$, obtained from the static load test (Table 5). The graph shows that the deformation energy $V_A$ is greater than the kinetic energy $T_A$. The reason for this is that the static load test was preceded by the dynamic load test, which causes a significant additional sampler penetration into the soil, changing the soil condition of the static test.

the load corresponding to the settlement equal to the permanent penetration corresponding to the last impact. The last column in Table 5 shows the values of the deformation energy $V_A$, which is equal to the numeric integration of the load-settlement curve, up to the displacement equal to the permanent penetration corresponding to the last impact.

The settlements measured during the static load test have not been adjusted to take into account possible displacements of the reference level, placed on the ground surface 0.25 m away from the borehole axis. The applied force magnitude includes the weights corresponding to the rods, load cell, hydraulic jack and ball-joint.

**Test Data Analysis**

Figure 7 shows a comparison between the kinetic energy $T_A$, measured during the dynamic test (Table 4) and the deformation energy $V_A$, obtained from the static load test (Table 5). The graph shows that the deformation energy $V_A$ is greater than the kinetic energy $T_A$. The reason for this is that the static load test was preceded by the dynamic load test, which causes a significant additional sampler penetration into the soil, changing the soil condition of the static test.
Table 5. Static load test results

<table>
<thead>
<tr>
<th>Case</th>
<th>Maximum load (kN)</th>
<th>Maximum settlement (mm)</th>
<th>Load (kN)</th>
<th>Settlement (mm)</th>
<th>Energy $V_A$ (J)</th>
</tr>
</thead>
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<tr>
<td>1</td>
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<td>9.3</td>
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<td>295</td>
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<td>3.8</td>
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<td>3.78</td>
<td>55</td>
<td>202</td>
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<td>59.0</td>
<td>4.35</td>
<td>46</td>
<td>193</td>
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<td>5.5</td>
<td>44.2</td>
<td>5.49</td>
<td>33</td>
<td>177</td>
</tr>
</tbody>
</table>

Table 6. Estimated efficiencies in terms of work done in the dynamic test and in the static test

<table>
<thead>
<tr>
<th>Case</th>
<th>Dynamic work $W_A$ (J)</th>
<th>Static work $W_A$ (J)</th>
<th>Dynamic Efficiency $\eta^d$ (%)</th>
<th>Static Efficiency $\eta_s$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>263</td>
<td>295</td>
<td>55</td>
<td>62</td>
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<tr>
<td>2</td>
<td>214</td>
<td>209</td>
<td>45</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>180</td>
<td>202</td>
<td>38</td>
<td>42</td>
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<tr>
<td>4</td>
<td>146</td>
<td>193</td>
<td>31</td>
<td>40</td>
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<tr>
<td>5</td>
<td>166</td>
<td>177</td>
<td>35</td>
<td>37</td>
</tr>
</tbody>
</table>

Fig. 7. Comparison between the kinetic energy $T_A$ and the deformation energy $V_A$

Table 6 shows the efficiency values evaluated from the work done by the non-conservative forces, according to Eq. (18).

It can be observed that the static efficiency is slightly higher than the dynamic one, similarly to the energy values (see Fig. 8), for the same reason. Also, it can be observed that both the dynamic efficiency and the static efficiency values are low when compared with those usually obtained in the Brazilian practice.

Belincanta (1998) has found that for a 14 m long rod, the average efficiency is 73%, and that extrapolating the values for longer rods, the average efficiency will be 81.9%, very close to the one obtained by Cavalcante (2002). For rod lengths varying from 2 to 14 m and $N_{SPT}$ ranging from 2 to 64, Cavalcante (2002) obtained 82.3% for the average efficiency.

Table 7. Static resistance values: estimated and measured in the static load test

<table>
<thead>
<tr>
<th>Case</th>
<th>Theoretical $N_{SPT}$ Displacement (mm)</th>
<th>$R_s$ (kN)</th>
<th>$R_s$ (kN)</th>
<th>$R_s$ (kN)</th>
<th>Static load test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.78</td>
<td>35</td>
<td>6.82</td>
<td>7.51</td>
<td>9.30</td>
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<td>2</td>
<td>4.29</td>
<td>60</td>
<td>3.06</td>
<td>3.57</td>
<td>3.56</td>
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<tr>
<td>3</td>
<td>5.63</td>
<td>55</td>
<td>3.38</td>
<td>3.27</td>
<td>3.78</td>
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<td>6.43</td>
<td>46</td>
<td>3.13</td>
<td>3.17</td>
<td>4.35</td>
</tr>
<tr>
<td>5</td>
<td>7.24</td>
<td>33</td>
<td>4.01</td>
<td>5.03</td>
<td>5.49</td>
</tr>
</tbody>
</table>

Fig. 8. Comparison between the estimated resistance and the measured resistance in the static load test (regular scale)

Fig. 9. Comparison between the estimated resistance and the measured resistance in the static load test (magnified scale)

Table 6 confirms that it is also possible to evaluate the impact efficiency from the work done during the static load test on the SPT sampler. Table 7 shows the static resistance values assessed by means of Eqs. (17) and (18), using the efficiency values shown in Table 6 and the values measured in the static load tests, for static displacements equal to displacements measured in the dynamic test.

The $N_{SPT}$ index value measured can be found in the fifth column of Table 3. The first column of Table 7
shows the same value in the format of a theoretical $N_{SPT}$ index equivalent to a penetration of 0.30 m. Table 7 corroborates that it is possible to convert the $N_{SPT}$ index into a sampler penetration resistance at test depth.

Figures 8 and 9 show a comparison between the static resistance values, assessed by means of Eqs. (17) and (18), and the ones measured during the static load tests. This figure also shows the static resistance values presented by Cavalcante (2002), assuming the efficiency $\eta^*$ equal to 70%. There is a lack of data corresponding to the resistance range from 20 to 80 kN, as a consequence of the particular conditions of the sites where the tests were performed. It can be observed that the measured resistance in the static load test is slightly higher than those resistances assessed by Eqs. (17) and (18), as it was previously explained.

CONCLUSIONS

From the data analysis and comparison with the data obtained using the SPT analyzer, regarding unsaturated sandy soils, the following conclusions can be inferred:

• The application of Hamilton’s Principle to energy transformations which occurred during the hammer impact in standard penetration tests was verified.

• The static resistance can be evaluated from the $N_{SPT}$ index, using either Eq. (16) or Eq. (17).

• The static load tests show that the deformation energy stored in the system has been transformed into work done by non-conservative resisting forces.

• It is possible to evaluate the impact efficiency from the work done during the static load test on the SPT sampler.

Finally, additional researches are necessary to confirm the applicability of the previously described procedures in this paper, for different kinds of soils. In addition, tests performed below the water level should be considered.

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REFERENCES


