

# Maximum Envelope of Lateral Resistance through Dynamic Increasing Energy Test in Piles

R.M. Valverde, F. Massad

**Abstract.** The traditional dynamic load test, based on the one-dimensional wave propagation theory consists in applying a sequence of constant energy blows and making measurements using deformation and acceleration sensors installed on top of the pile, as a function of time. The traditional method has evolved with the development of a numerical model that simulates the Static Load Test (SLT) of a pile dynamically tested. Another evolution was the introduction of the Dynamic Increasing Energy Test (DIET) created and proposed by Aoki (1997). The present study is an initiative to deepen the increasing energy method focusing on the definition of the maximum lateral resistance envelope, allowing the recovery of the mobilized resistance along the shaft, lost in blows prior to the maximum applied energy, especially in layers close to the top of the pile. This procedure is called the Maximum Envelope of Lateral Resistance. Two case studies are presented, in which static and dynamic tests were performed on the same pile. The application of the Maximum Envelope of Lateral Resistance, also referred to as Maximum Envelope Method, led to a definition of higher load capacities through the CAPWAP analysis, with simulated load-displacement curves with good correlations in comparison with the Static Load Tests (SLT). When performed after several rest periods, the Maximum Envelope Method allows an assessment of the “set up” development over time.

**Keywords:** dynamic load test, increasing energy, lateral resistance, load capacity, maximum envelope.

## 1. Introduction

The PDA (“Pile Driving Analyzer”) signal of the hammer blow associated to the highest pile capacity during the dynamic load test is the one chosen to be analyzed by CAPWAP (Case Pile Wave Analysis Program). This program provides a simulation of the Static Load Test (SLT) and allows determining the mobilized shear and toe resistances as if the pile had received only that single blow since the end of its installation, without considering changes in soil properties caused by earlier blows of lower energies. However, at each applied blow, the shear and toe resistances change due to effects on the soil, particularly on those with high sensitivity. Therefore, to consider only the last blow as the one in which the maximum capacity occurs is a practice that generates simplified interpretations regarding the pile load capacity and the lateral friction along the pile shaft. The Maximum Envelope Method has the objective of evaluating the whole Dynamic Increasing Energy Test (DIET), considering the effects of the blows applied prior to the one with the maximum mobilization of static resistance. This allows recovering as much information as possible about the load capacity in a Dynamic Increasing Energy Test (DIET), including: a) a top load-settlement curve simulated through the mathematical model of Coyle and Reese (1966); and b) an assessment of the “set up” development over time in sensitive soils.

## 2. Dynamic Load Test and CAPWAP

The dynamic load test consists in applying a sequence of blows on the pile and measuring values of specific deformation and acceleration over time through force transducers and high sensitivity accelerometers. These instruments are installed at a minimum distance from the top established by standard. After applying the blows, the recorded data are sent to the PDA, which calculates the force and velocity curves of the recorded blows. The data acquired in the field can later be analyzed by CAPWAP, a computer program whose results include a simulated static analysis of the load-set curve and the distribution of resistances along the pile shaft and toe. The wave equation is solved using one variable as input (velocity or force) and computing the other variable. The results are based on the quality of the match between the curves of the calculated and the measured variables, called “*Match Quality*”. CAPWAP allows calculating tensions and movements by dividing the pile into segments of known properties (elastic modulus and mass density). The propagations of the descending and ascending waves (“*Wave down*” and “*Wave Up*”) are recorded and their superposition is done according to the wave equation, in which the ascending and descending forces are summed and the velocities are equal to their differences divided by the impedance of the pile in each segment. The displacement and velocity of each pile segment

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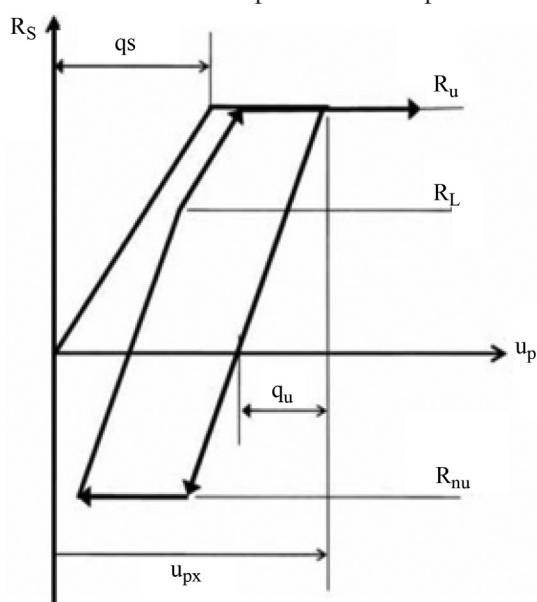
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are the basis for determining the soil resistance. The soil model, introduced by Smith (1960), consists in an elasto-plastic spring and a linear dashpot. The total static load capacity is the sum of the static resistances of the shaft and pile toe segments.

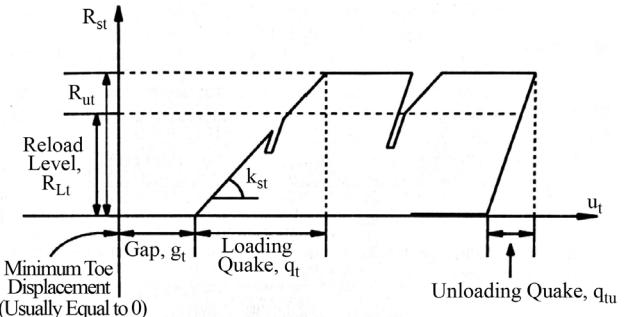
Figure 1 illustrates the association between the basic static resistance and the pile shaft displacement. In the loading phase, as a pile segment moves downward, the static resistance increases linearly over a quake distance  $q_s$  up to the maximum shaft resistance value  $R_u$ , and then it remains constant until the maximum displacement  $u_{px}$  on this element is reached. Next is the unloading phase, with a slope defined by the "unloading quake"  $q_u$  up to a negative ultimate resistance level  $R_{nu}$ , which is the minimum limit defined by the product of  $R_u$  and an unloading multiplier  $U_n$  (Rausche *et al.*, 2010).

For the static pile toe resistance, there is a similar association except for the unloading phase, in which the toe resistance is zero ( $U_n$  value is 0). As the pile toe moves downward, the resistance may eventually remain zero due to some existing gap ("Resistance toe gap"), represented by  $t_g$  and then increases linearly over a quake distance  $q_t$  ("loading toe quake") until it reaches the maximum toe resistance  $R_{ut}$ , and remains constant up to a maximum displacement  $u_t$  (Fig 2). For total toe resistance activation, the pile toe displacement must be greater than the sum of the quake  $q_t$  and the toe gap  $t_g$ .

This model even allows considering a soil mass embedding on the shaft or pile toe. In order to be able to match certain signals, it was necessary to include an extension of the soil model called "Radiation Damping", necessary in cases when displacements are small and the soil practically moves with the pile. An example is a pile partially embedded on hard rock. As the pile exerts compression forces



**Figure 1** - Static shaft resistance-displacement - CAPWAP soil model (Pile Dynamics 2006).



**Figure 2** - Toe static resistance-displacement - CAPWAP soil model (Pile Dynamics 2006).

against the rock, a wave is generated in the rock and the soil resistance appears to be a function of the velocity rather than the displacement (Pile Dynamics, 2006).

The balance of forces and displacements at the top is computed by ignoring the viscous effects of the soil (Rausche *et al.*, 1994). The results of the CAPWAP signal matching process are primarily ultimate resistance values and quakes (and therefore soil stiffness). Together with the pile stiffness, CAPWAP produces a simulated static load-set curve. Such procedure yields important limitations that should be considered:

- (i) the simulated static load-set curve represents a load test that was performed during a fraction of a second; for that reason, the result cannot include displacements caused by consolidation of soil layers below or around the pile;
- (ii) the calculated static load-set curve refers to the time of the dynamic testing and may differ from the Static Load Test (SLT) curve with longer waiting time; and
- (iii) for concrete piles, the elastic modulus used in the calculation of the static load-settlement curve is the same as that determined by the PDA. Static elastic moduli are generally lower than the dynamic moduli and the static analysis options allow for an input of pile modulus reduction factor, as stated in the CAPWAP manual (Pile Dynamics, 2006).

### 3. Maximum Envelope Method

The main objective of the Maximum Envelope Method is to analyze all the blows applied during the Dynamic Increasing Energy Test (DIET). Rausche *et al.* (1994) state that the distribution of ultimate shaft resistance forces of all segments can be directly determined from the record portion between the time of impact and the time of the first wave return. This procedure is applied to all blows of the DIET allowing to calculate the maximum envelope of the shaft resistance distribution and, additionally, the maximum toe resistance. These results, together with soil profile, make it possible to estimate elasto-plastic load transfer functions for each soil layer, also known as  $q-z$  and  $t-z$  functions, as shown in Figs. 1 and 2. In this paper only the loading phase will be considered.

The authors applied the Coyle-Reese method to simulate the static load-set curve using these elasto-plastic load transfer functions, in order to validate the results obtained through the Maximum Envelope Method. The validation is accomplished comparing the resulting curve with the Static Load Test (SLT) curve. In the Coyle-Reese method the pile is divided into segments with their respective load transfer functions. Its application initiates from the last element of the pile assuming that the pile toe has moved a small displacement  $y_t$  downward. Through the pile toe load transfer function, the toe resistance  $Q_p$  is determined. Then, forces and displacements of upper segments are calculated iteratively up to the top using the lateral load transfer functions and considering the elastic shortening of the pile together with the balance of acting forces, in order to obtain one point of the load-settlement curve. This process is iteratively repeated, assuming different pile toe displacements  $y_t$ , to obtain several points of the load-set curve until the maximum lateral friction (determined by the Maximum Envelope Method) of all soil segments is reached.

The number of segments in the Coyle-Reese method should be the same or greater than the number of soil layers determined by local geotechnical tests, like the Standard Penetration Test (SPT). Each blow applied during the Dynamic Increasing Energy Test (DIET) indicates different values of lateral resistance and, therefore, different skin friction  $f_s$  and quake  $q_s$  values. According to Fig. 3, the max-

imum skin friction value  $f_{\max}$  of each soil layer is the average of the greatest  $f_s$  values calculated through the CAPWAP, considering all applied blows during the DIET, in accordance with the Maximum Envelope Method, described above.

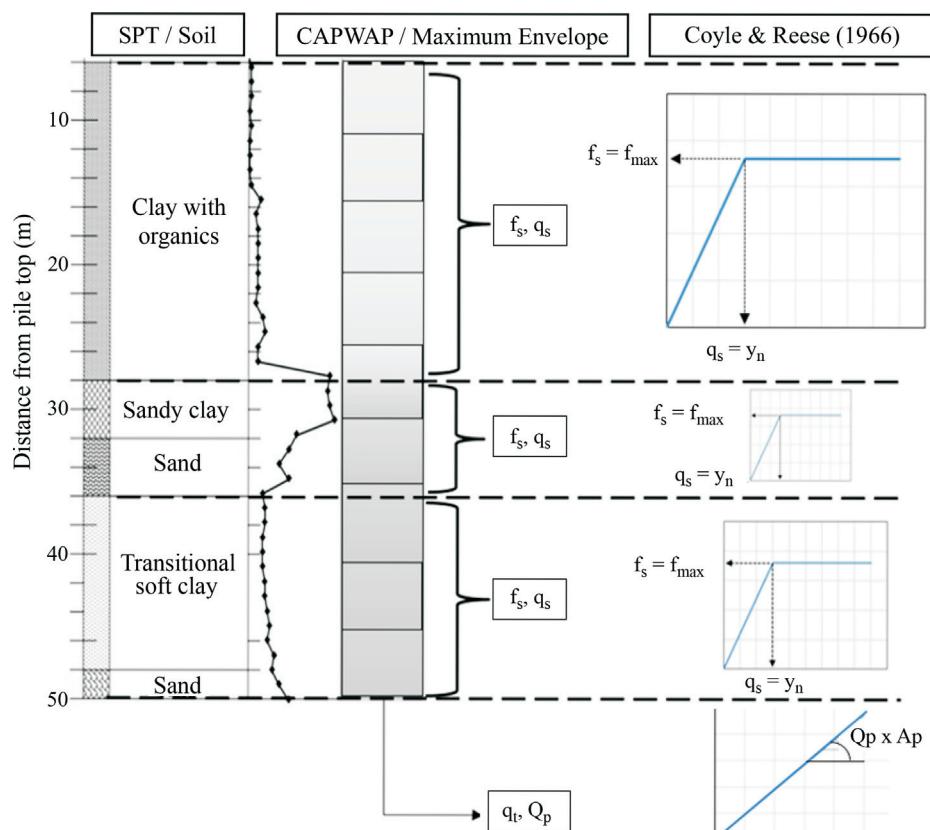
#### 4. First Case: Port Terminal - Santos, SP - Brazil

##### 4.1. Pile and subsoil profiles

The first case studied refers to a pile (EC1304) of a terminal port at the Santos Coastal Plain ("Baixada Santista"), Brazil. It was a precast concrete pile, circular, with an outer diameter of 80 cm, a wall thickness of 15 cm and a nominal cross-sectional area of 3062.05 cm<sup>2</sup>. The pile had a total length of 52.0 m, in which 43.4 m have penetrated in the soil. These and other characteristics are shown on Table 1.

The pile was driven offshore, on May 29th, 2012, using a 160 kN Junttan HHK hydraulic hammer. During the initial 20 m, the pile penetrated the soil with an approximately constant rate of 50 cm for every 20 blows applied and, from this point on, with the same number of blows, the penetration reduced to 20 cm until reaching the final depth with 43.4 m of its length.

The soil profile was determined from several field tests 6 m below sea water level. The subsoil is composed



**Figure 3** - Relationship between soil profile, maximum envelope results and Coyle-Reese load transfer functions.

**Table 1** - EC1304 pile profile and PDA data.

| Pile name | Diameter     |             | Length    |                   |              | Wave speed<br>(m/s) | Dynamic modulus<br>(GPa) |
|-----------|--------------|-------------|-----------|-------------------|--------------|---------------------|--------------------------|
|           | Outside (cm) | Inside (cm) | Total (m) | Below sensors (m) | Embedded (m) |                     |                          |
| EC1304    | 80.0         | 50.0        | 52.0      | 50.8              | 43.40        | 3700                | 34.2                     |

initially by a 20 m thick very soft organic marine clay, locally known as SFL Clay (Fluvio Lagunar Sediment), which is generally slightly overconsolidated (OCR~1.1 to 1.5), followed by a medium to compact clayey sand (SPT ranging from 7 to 33 blows), about 8 m thick. These soils overlie 4 m of an overconsolidated clay, with OCR greater than 2.5 due to a great sea level lowering during the last glaciation, known locally as Transitional Clay (AT), with SPT higher than 5. Finally, at depth greater than 32 m below seabed occur thin to thick layers of compact sand, with SPT of the order of 10. More detailed information about the origin and composition of these soils can be found in Massad (2009).

#### 4.2. Static Load Test (SLT)

The Static Load Test (SLT) was performed on August 7 and 8, 2012, about 70 days after pile installation, using a set of pumps, hydraulic jack and pressure gauge supported on a block of concrete and 4 reaction piles. Known as Mixed Maintained Load, the test consisted of slow applications of load increments during the loading phase and quick unload during the unloading phase, according to NBR 12131 (2006). The maximum load and displacement in the Static Load Test (SLT) were 8407 kN and 34 mm, respectively, without indication of failure and the permanent set was 6 mm, as shown in Fig. 4.

#### 4.3. Dynamic Increasing Energy Test (DIET) and CAPWAP

Pile EC1304 was dynamically tested on June 6, 2012, therefore about 8 days after its installation. Blows with the following hammer drop heights were applied: 20; 40; 60; 80; 100; 120; 120; 120 and 120 cm. The last applied blow corresponding to the highest mobilized resistance was used for the first CAPWAP analysis. Table 2 provides some of the numerical results obtained from the “best match quality” of CAPWAP analysis.

Figure 4 shows visually an excellent correlation between the curve simulated by the CAPWAP and the curve obtained from Static Load Test (SLT).

**Table 2** - CAPWAP analysis results - Pile EC1304.

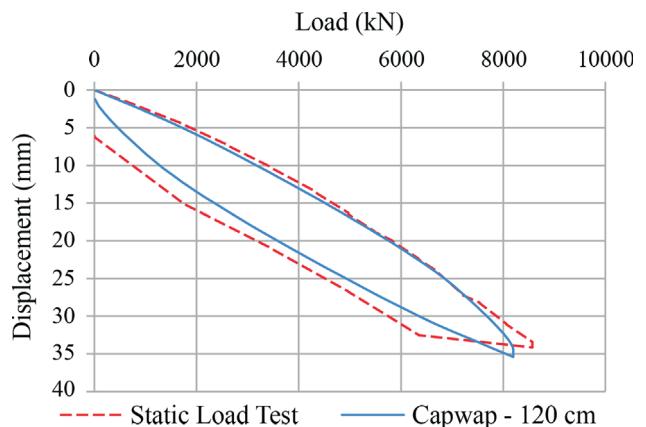
| Pile name | Total capacity<br>(kN) | Lateral resistance |      |     | Toe resistance |     | Shaft quake<br>(mm) | Toe quake<br>(mm) |
|-----------|------------------------|--------------------|------|-----|----------------|-----|---------------------|-------------------|
|           |                        | (kN)               | (kN) | (%) | (kN)           | (%) |                     |                   |
| EC1304    | 8044                   | 6206               | 77   |     | 1838           | 23  | 2.31                | 3.32              |

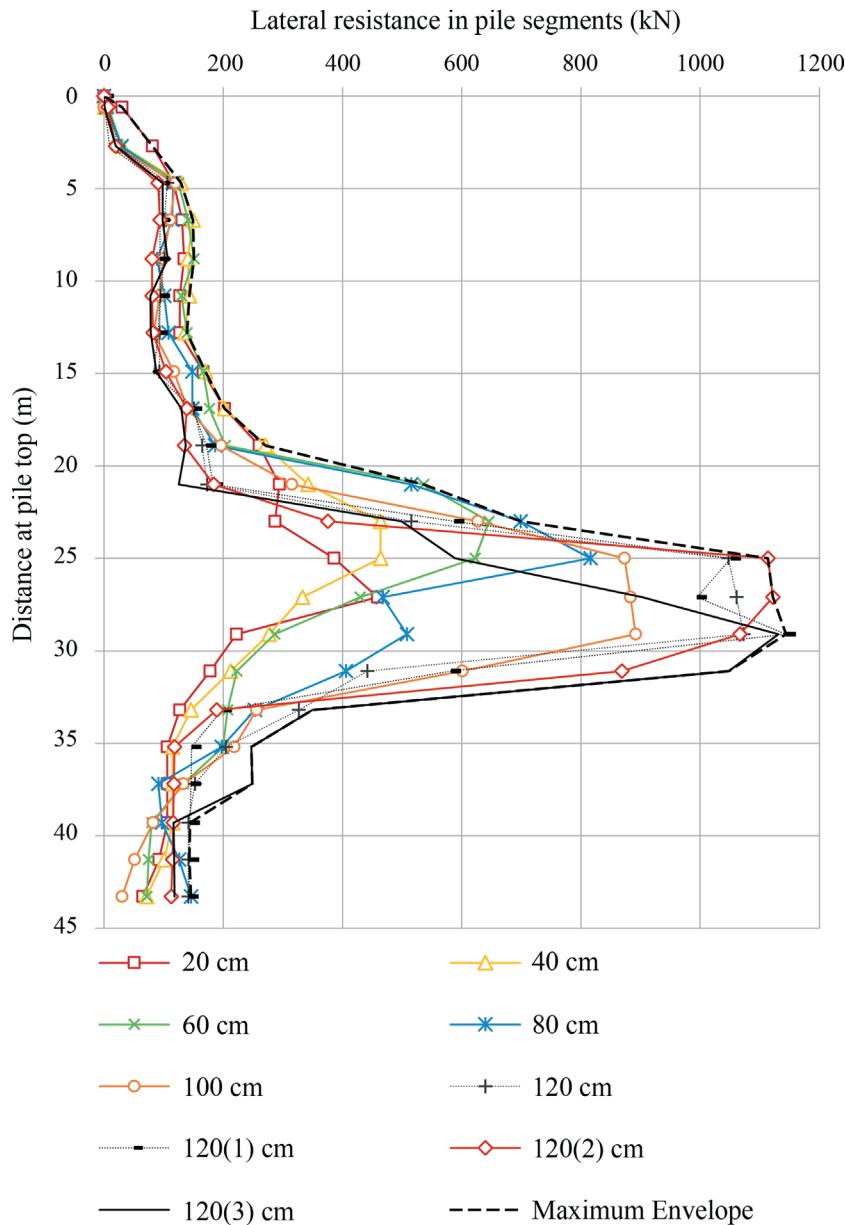
#### 4.4. Maximum envelope of lateral resistance - EC1304

Figure 5 shows the lateral resistance in pile segments distributed along depth given by the CAPWAP for each applied blow. It is possible to notice that in the first half of the pile the maximum values of lateral friction are associated with lower energy blows. In the lower half, such maximum lateral resistances are reached with higher energy blows.

After each new applied blow, the soil undergoes changes and loses part of the resistance recovered during the “set up”. Figure 5 allows to compare the lateral resistance of the last blow (120<sup>(3)</sup> cm) with the Maximum Envelope, highlighted in dashed line. The envelope of lateral resistance of EC1304 pile allows some considerations regarding lateral resistance: (i) blows with hammer drops of 20 cm to 80 cm indicate greater static lateral resistances up to approximately 24 m; (ii) the first 20 m show a gradual reduction of lateral resistance as the hammer drop heights increase, up to a minimum limit of lateral resistance; (iii) the last blow (120<sup>(3)</sup> cm), represented with a full black line, is at the minimum limit of the mobilized lateral resistance in the upper segments, until approximately 22 m.

Using the dashed line of Fig. 5, *i.e.*, the Maximum Envelope of Lateral Resistance, associated with the highest mobilized toe resistance (blow 120<sup>(3)</sup> cm), the total pile capacity was estimated as 10085 kN. Figure 6 shows the curves simulated by CAPWAP considering as the starting

**Figure 4** - Simulated CAPWAP and Static Load Test curves - blow 120 cm - EC1304.



**Figure 5** - Lateral resistance distribution - EC1304.

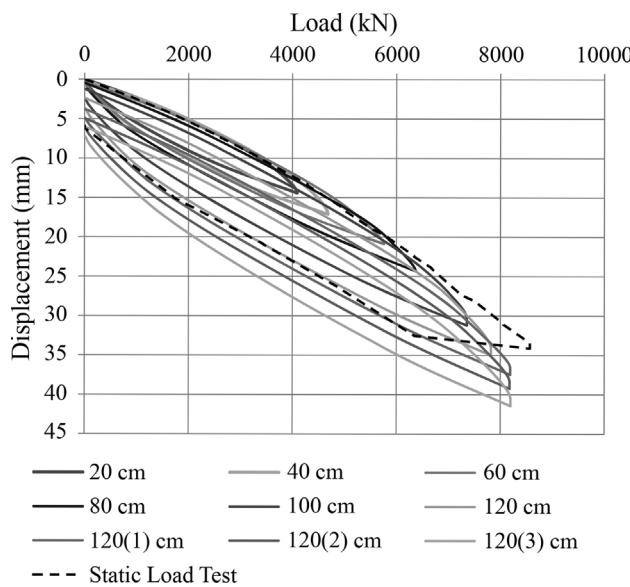
point of each applied blow the final point of the precedent blow, like a cyclic monotonic test. The set of simulated CAPWAP curves maintain a good visual correlation with the Static Load Test (SLT). It is possible to notice that there was no evidence of failure, as emphasized previously.

#### 4.5. Coyle-Reese method using the last applied blow ( $120^{(3)}$ cm)

For the application of the Coyle-Reese method to the last blow ( $120^{(3)}$  cm) using CAPWAP results, the part of the pile embedded in the soil was divided into 5 segments, the same number of layers identified in the soil profile, as shown in Table 3. In this table, the shaft quake  $q_s$  was assumed constant indicating the full activation of lateral resistance throughout the pile length. Furthermore, the toe

quake was figured out as 3.3 mm with 1838 kN of toe resistance. The static elastic modulus of the pile was figured out as 27.8 GPa, *i.e.*, 86% of the dynamic modulus (see Table 1), according to Lydon and Balandran (1986) empirical relation. The last column of Table 3 shows the “elastic” parameter B of each load transfer function. The pile length above ground was 8.6 m.

The result of Coyle-Reese method is shown in Fig. 7. The total capacity by the Coyle-Reese method was estimated at 8029 kN with 38 mm of displacement. The load-set curve was adjusted considering the elastic shortening of the part of the pile above the sea bed in order to simulate the same conditions of the Static Load Test (SLT), which added 10 mm in the last point of the curve. The Coyle-Reese curve of Fig. 7 is close to the curves of the static load

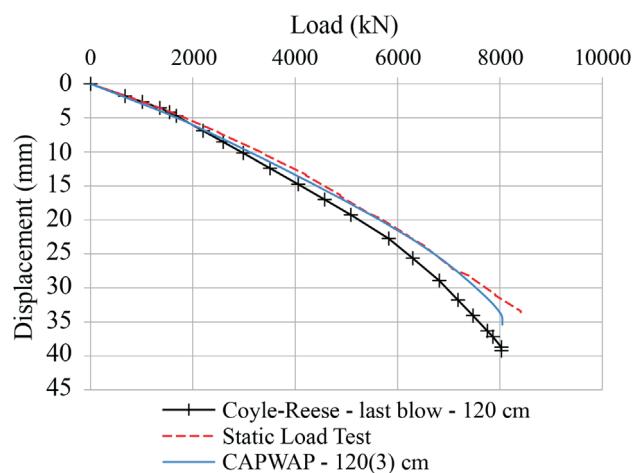


**Figure 6** - Simulated static curves from CAPWAP vs Static Load Test - EC1304.

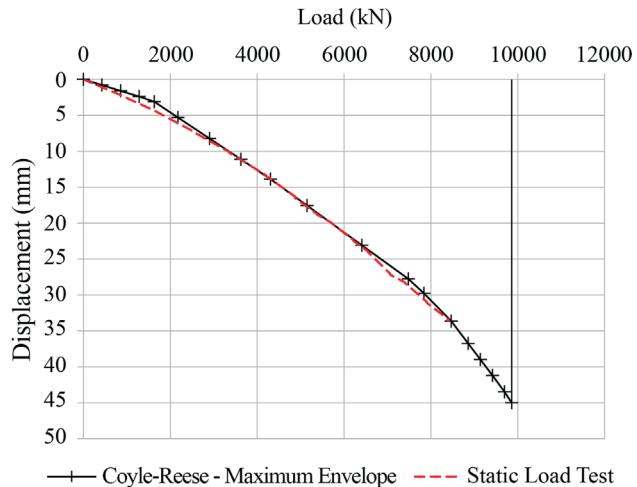
test and the simulated static curve from CAPWAP, at least up to the 4000 kN load.

#### 4.6. Coyle-Reese method using maximum envelope results

For this new Coyle-Reese application, the mean lateral friction of each soil layer was determined using the dashed line of Fig. 5 and is shown in Table 4, together with the values of the mean shaft quakes. The result is presented in Fig. 8, which reveals excellent correlation between the Coyle-Reese simulated curve using Maximum Envelope results and the Static Load Test (SLT). In addition, the total capacity from the Coyle-Reese curve was 9863 kN with 45 mm of displacement. This total capacity is close to



**Figure 7** - Simulated load-set curves vs. Static Load Test - EC1304.



**Figure 8** - Simulated load-set curve vs. Static Load Test - EC1304.

**Table 3** - Input data for the Coyle-Reese method - last applied blow (120<sup>(3)</sup> cm) - EC1304.

| No. | Soil Layer        | $\Delta H$ (m) | $f_{max}$ (kPa) | $y_n$ (mm) | $B = f_{max}/y_n$ (kPa/mm) |
|-----|-------------------|----------------|-----------------|------------|----------------------------|
| 1   | SFL Clay          | 20             | 17.7            | 2.308      | 7.7                        |
| 2   | Clayey sand       | 4              | 60.0            | 2.308      | 26.0                       |
| 3   | Transitional clay | 8              | 176.3           | 2.308      | 76.4                       |
| 4   | Medium sand       | 10             | 41.5            | 2.308      | 18.0                       |
| 5   | Compact sand      | 2              | 22.7            | 2.308      | 9.8                        |

**Table 4** - Input data for the Coyle-Reese method - Maximum Envelope - EC1304.

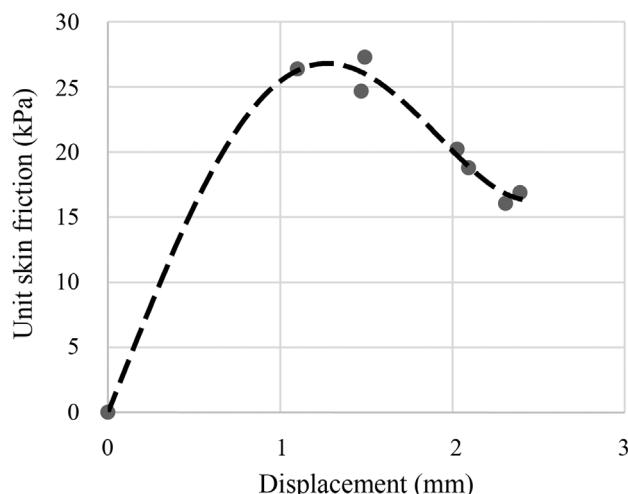
| No. | Soil layer        | $\Delta H$ (m) | $f_{max}$ (kPa) | $y_n$ (mm) | $B = f_{max}/y_n$ (kPa/mm) |
|-----|-------------------|----------------|-----------------|------------|----------------------------|
| 1   | SFL Clay          | 20             | 28.8            | 1.25       | 23.1                       |
| 2   | Clayey sand       | 4              | 116.4           | 1.7        | 68.5                       |
| 3   | Transitional clay | 8              | 208.8           | 2.46       | 84.9                       |
| 4   | Medium sand       | 10             | 42.3            | 1.75       | 24.2                       |
| 5   | Compact sand      | 2              | 27.9            | 0.234      | 119.3                      |

10085 kN, estimated in section 4.4, using the Maximum Envelope of Lateral Resistance.

In order to show the difference of the unit skin friction values of the SFL Clay layer between the CAPWAP of the last blow and the Maximum Envelope method, Fig. 9 shows the average load transfer function calculated with CAPWAP results of all applied blows during the dynamic load test. The peak of the curve, with unit skin friction of 28.8 kPa and displacement of 1.25 mm, corresponds to the values of  $f_{max}$  and  $y_n$  of Table 4. For displacements above roughly 2.3 mm, the curve tends to a residual value indicating a condition close to a remolded soil; this value was used in the Coyle-Reese method for the last applied blow (120<sup>(3)</sup> cm).

#### 4.7. Summary of static resistance results - EC1304

Table 5 summarizes the results obtained for the first case, related to the static resistances. Notice that the toe re-



**Figure 9** - Average load transfer function for the SFL Clay from Max. Envelope Method.

**Table 5** - Final results - EC1304.

| Test/method                      | Static resistance (kN) |       |       |
|----------------------------------|------------------------|-------|-------|
|                                  | Shaft                  | Toe   | Total |
| Static Load Test (SLT)           | -                      | -     | 8407  |
| CAPWAP - 120 <sup>(3)</sup>      | 6206                   | 1838* | 8044  |
| Maximum envelope                 | 8247                   | 1838* | 10085 |
| Coyle-Reese - 120 <sup>(3)</sup> | 6191                   | 1838* | 8029  |
| Coyle-Reese - maximum envelope   | 8025                   | 1838* | 9863  |

**Table 6** - PC01 pile profile and PDA data.

| Pile name | Diameter     |             | Length    |                   |              | Wave speed<br>(m/s) | Dynamic modulus<br>(GPa) |
|-----------|--------------|-------------|-----------|-------------------|--------------|---------------------|--------------------------|
|           | Outside (cm) | Inside (cm) | Total (m) | Below sensors (m) | Embedded (m) |                     |                          |
| PC01      | 91.4         | 88.2        | 40.1      | 36.14             | 33.30        | 5123                | 210.9                    |

sistance has the same value, determined by CAPWAP applied to the last blow (120<sup>(3)</sup> cm). The total static resistances from this single blow (CAPWAP 120<sup>(3)</sup>) and from the Static Load Test (SLT) differ by no more than 8044/8407-1  $\cong$  4%. Moreover, compared with CAPWAP 120<sup>(3)</sup> cm, the Maximum Envelope Method allows estimating a lateral resistance increment of 8247 - 6206 = 2041 kN.

#### 5. Second Case: Steel Tube Pile in Port - Santos, SP - Brazil

##### 5.1. Pile properties

The second case refers to a test pile for the construction of a pier in the Piaçaguera Chanel, close to Cubatão City in the Santos Coastal Plain (“Baixada Santista”), Brazil. The tests were performed on a steel tube driven pile, with external diameter of 91.4 cm and wall thickness equal to 16 mm, resulting in a section steel area of 451.4 cm<sup>2</sup>. The pile (PC01) was submitted to Static Load Test (SLT) and to Dynamic Increasing Energy Tests (DIET) and its characteristics are detailed in Table 6.

The pile was installed on February 11, 2015, using a 90 kN Junttan HHK hydraulic hammer. Dynamic load tests were performed after the end of driving (EOD) and after several rest periods: 3 h, 6 h, 24 h, 48 h and 216 h (9 days). The objective was to analyze the “set up” effect of the soil and to estimate the long term lateral resistance, applying the Maximum Envelope Method. The Static Load Test was performed three months after the DIETs, using the Slow Maintained Load procedure in accordance to NBR 12131 (ABNT 2006).

The subsoil profile is composed initially by a 6 m fill layer of clayey sand m (SPT~1 to 10), followed by (i) a soft layer of the SFL Clay (18 m thick and SPT~2 to 4), and (ii) 6 m of fine to coarse sand, with gravel, SPT ranging from 15 to 30. Below about 30 m there is a layer of fine to coarse clayey sand, 8 m thick (SPT~12 to 30), overlying gneiss. The SFL Clay layer may be subdivided in two sublayers, half with SPT  $\cong$  2 and half with SPT  $\cong$  4.

##### 5.2. Dynamic Increasing Energy Tests (DIET) and CAPWAP - 216 h

Dynamic Increasing Energy Tests (DIETs) were performed at the end of driving and in all “set up” periods. Blows with the following hammer drop heights were applied: 20; 40; 60; 80; 100 and 120 cm. The results of the CAPWAP analysis of the last blow after the 216 h “set up” time are shown in Table 7 and in Fig. 10.

This test was performed on 02/20/2015, three months before the Static Load Test (SLT), which justifies the difference between the maximum displacements shown in Fig. 10: 28 mm in the Static Load Test (SLT) against 35 mm in the dynamic test.

### 5.3. Maximum envelope of lateral resistance - 216 h

The Maximum Envelope result for the 216 h “set up” period is shown in dashed line in Fig. 11, together with the distribution of lateral resistance in pile segments along depth for various hammer drop heights. It can be noticed the same behavior of the first case, *i.e.*, as the applied energy increases, lower values of lateral static resistances are gradually mobilized in segments of the pile close the top, in contrast to higher values in segments close the pile toe.

Table 8 summarizes the static resistances and reveals an increase of  $5252/4647 - 1 \geq 13\%$  in the lateral resistance estimated with the Maximum Envelope Method compared to the single 120 cm CAPWAP analysis. Note that, main-

taining the same value for the pile toe, this amount drops to  $10164/9559 - 1 \geq 6\%$  for the total static resistance.

Figure 12 allows comparing the Maximum Envelope with the lateral resistance distributions obtained by the CAPWAP on the last blow (120 cm) at the end of driving and after 216 h rest period. At the end of the driving, a lateral resistance of 1381 kN was estimated by the CAPWAP. Using the data shown in Table 8, it may be concluded that the lateral resistance increased  $4647/1381 - 1 \geq 336\%$  for the last blow (120 cm) after the 216-h period (9 days) compared to  $5252/1381 - 1 \geq 380\%$  related to the Maximum Envelope.

### 5.4. “Set up” evaluation using the Maximum Envelope of Lateral Resistance - PC01

Dynamic load test results at all “set up” periods, presented in Table 9, indicate lateral and total resistance gains over time. This is also evident with the Maximum Envelope results.

The decreasing toe resistance values over time, observed in Table 9, indicate that the pile toe was not fully mobilized due to the lateral resistances increase along the pile shaft. Based on these results, Figs. 13 and 14 show variations of the  $Q/Q_0$  ratio for the lateral resistance and for the total capacity over time. In this relation,  $Q$  and  $Q_0$  are lateral resistance (Fig. 13) or load capacity (Fig. 14) after a certain period of rest and at the end of driving (EOD), respectively.

It is possible to notice that the lateral resistance increases significantly during the first 48 h and, after that, the increments are smaller and practically linear. An important factor to consider when evaluating the “set up” is the activation of all skin frictions during the dynamic test. Therefore, it is necessary to evaluate the shaft quake  $q_s$  of the last blow (120 cm) for each period of rest. If the result of the CAPWAP shows that the shaft quake does not remain constant and that from a certain depth it decreases, it may be

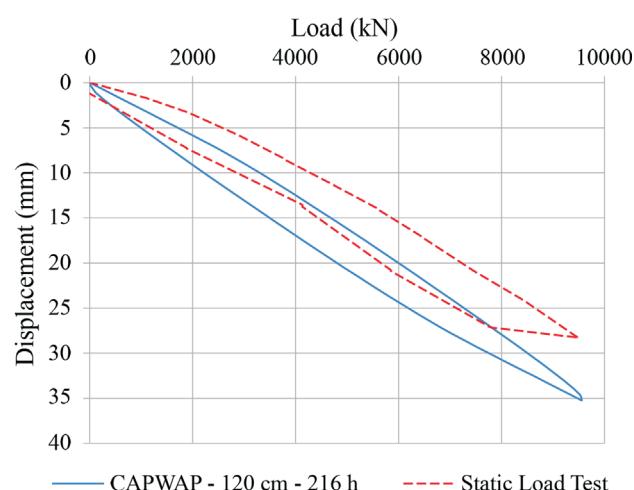


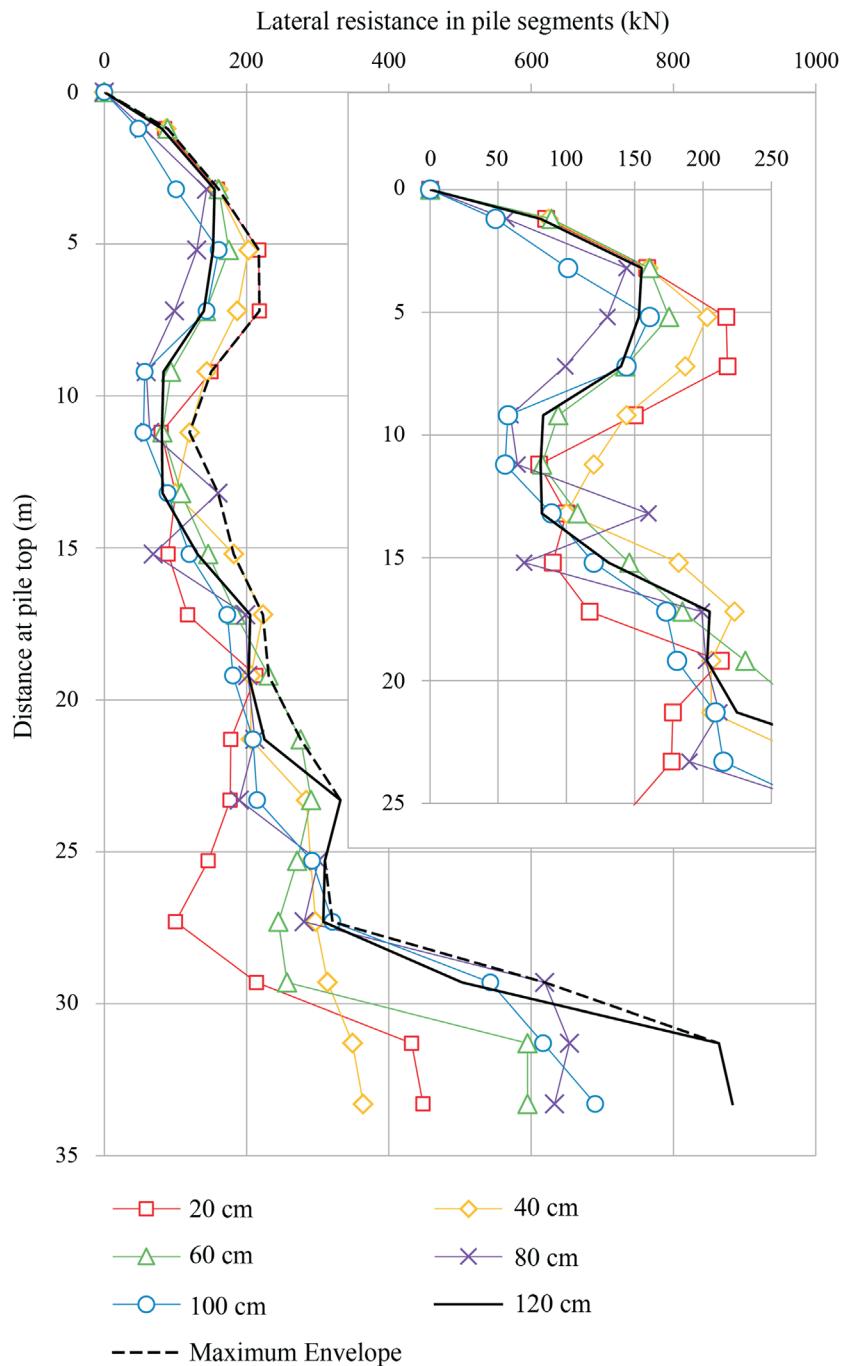
Figure 10 - Simulated CAPWAP and Static Load Test curves - 216 h “set up” - PC01.

Table 7 - CAPWAP Analysis results - PC01-120 cm blow and 216 h “set up” time.

| Pile name | Total capacity<br>(kN) | Lateral resistance |      |     | Toe resistance |     | Shaft quake<br>(mm) | Toe quake<br>(mm) |
|-----------|------------------------|--------------------|------|-----|----------------|-----|---------------------|-------------------|
|           |                        | (kN)               | (kN) | (%) | (kN)           | (%) |                     |                   |
| PC01      | 9559                   | 4647               | 48   |     | 4.912          | 52  | 5.73                | 1.75              |

Table 8 - Distribution of resistance along the pile - PC01-216 h “set up” time.

| Static<br>resistances | Hammer drop heights (cm) |      |      |      |      |      | Maximum<br>envelope |
|-----------------------|--------------------------|------|------|------|------|------|---------------------|
|                       | 20                       | 40   | 60   | 80   | 100  | 120  |                     |
| Lateral (kN)          | 3063                     | 3644 | 3867 | 3993 | 3938 | 4647 | 5252                |
| Toe (kN)              | 753                      | 2390 | 2528 | 4085 | 4530 | 4912 | 4912                |
| Total (kN)            | 3816                     | 6034 | 6395 | 8078 | 8468 | 9559 | 10164               |

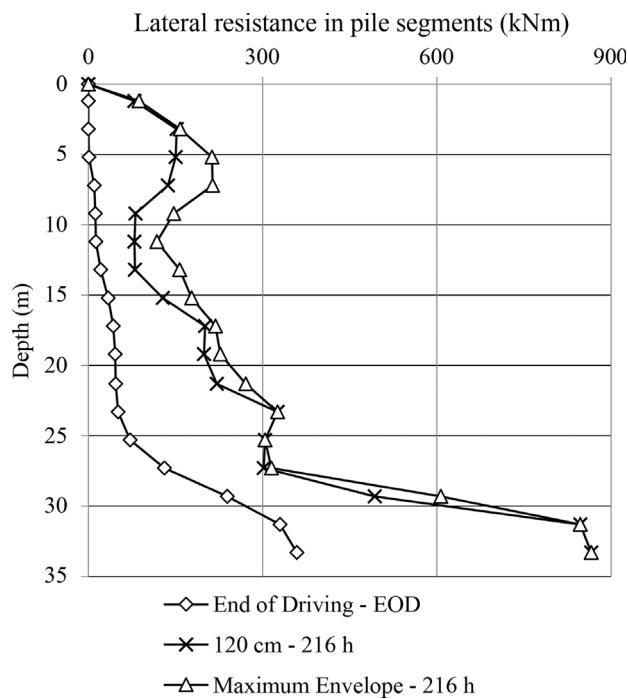


**Figure 11** - Lateral resistance distribution - 216 h “set up” time- PC01.

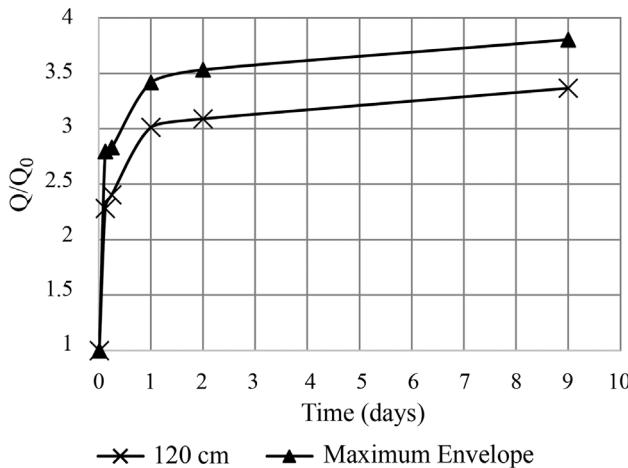
concluded that the applied energy was not enough to activate all lateral resistance. The shaft quake remained constant only within the EOD and the 3 h rest period. On longer periods,  $q_s$  decreased on segments near the pile toe. Thus, the results obtained for the evaluation of the “set up” can be considered underestimated, mainly in the last segments of the pile-soil system.

A more detailed and accurate evaluation of the skin friction gain can be achieved specifically for the SFL Clay, the predominant soil layer along the pile shaft. According

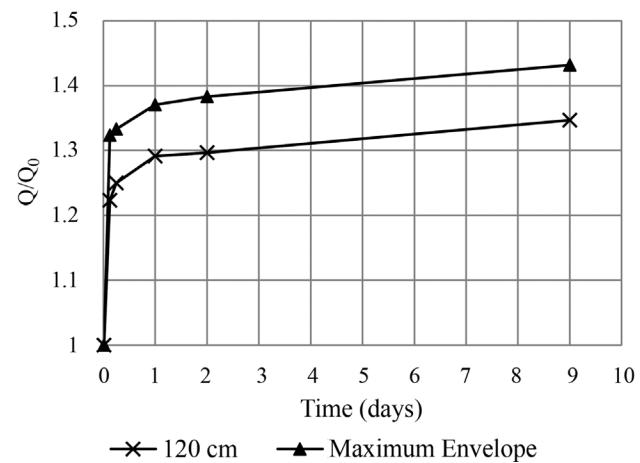
to the soil profile described, this layer lies between depths of -4.0 m and -24.0 m. Another important observation is that the shaft quake remained constant in all rest periods in this depth interval, which indicates that there was maximum skin friction mobilization. Figs. 15 and 16 show the  $f/f_0$  ratio over time only of the SFL Clay layer for both the Maximum Envelope and the blow of 120 cm. The  $f$  and  $f_0$  values refer to unit skin friction after a certain period of rest and at the end of driving (EOD), respectively.



**Figure 12** - Lateral resistance distribution -Max. Envelope, EOD and 216 h - PC01.



**Figure 13** - Results of lateral “set up” - 120 cm and Maximum Envelope - PC01.



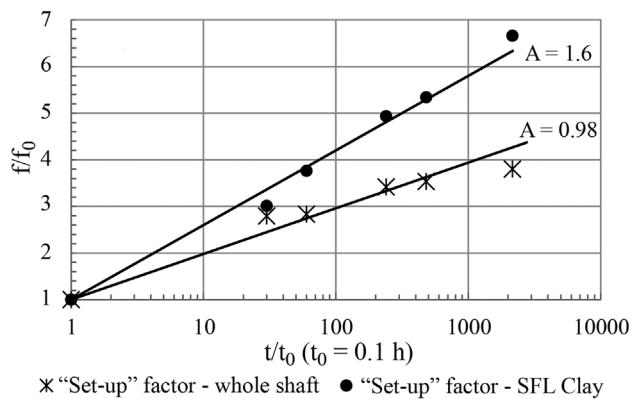
**Figure 14** - Results of total “set up” - 120 cm and Maximum Envelope - PC01.

Based on the results of the Maximum Envelope, it is possible to determine the parameter “A” of Bullock *et al.* (2005), which depends on the soil type, through the linear regression coefficients obtained in Fig. 15. This analysis shows that for the whole shaft the parameter “A” is equals to 0.98 and, for the SFL Clay layer alone, 1.6. This difference is due to the fact that the “A” parameter for the entire shaft includes “set up” of deep sandy layers, which have lower “set up” factors. With the same procedure and using only the 120 cm hammer drop blows, the parameters “A” are smaller compared to those obtained by the Maximum Envelope, as shown in Fig. 16. Among other publications, Bilfinger (2010) obtained the parameter “A” equal to 0.61 for skin friction in the Santos Coastal Plain (“Baixada Santista”) through dynamic Load Tests.

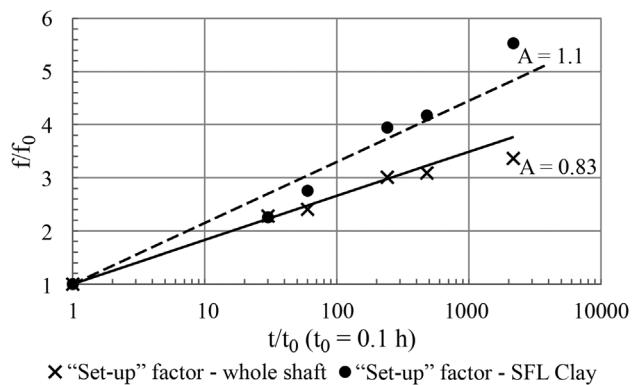
As an example of total lateral resistance “set up”, Figs. 15 and 16 show that the  $f/f_0$  ratio equals 2 in a rest period of 20 h considering only the blow of 120 cm, whereas through the Maximum Envelope method this same value would be reached in approximately 10 h.

**Table 9** - Summary of the results- PC01.

| No.   | 120 cm       |                        |            |                        | Maximum envelope |                        |            |                        |
|-------|--------------|------------------------|------------|------------------------|------------------|------------------------|------------|------------------------|
|       | Lateral (kN) | Resistance<br>Toe (kN) | Total (kN) | Quake on<br>shaft (mm) | Lateral (kN)     | Resistance<br>Toe (kN) | Total (kN) | Quake on<br>shaft (mm) |
| EOD   | 1381         | 5717                   | 7098       | 5.62                   | 1381             | 5717                   | 7098       | 5.62                   |
| 3 h   | 3149         | 5533                   | 8682       | 1.29                   | 3860             | 5533                   | 9393       | 3.25                   |
| 6 h   | 3321         | 5553                   | 8874       | 4.03                   | 3908             | 5553                   | 9461       | 3.47                   |
| 24 h  | 4159         | 5009                   | 9168       | 3.32                   | 4718             | 5009                   | 9727       | 2.66                   |
| 48 h  | 4265         | 4939                   | 9204       | 3.76                   | 4877             | 4939                   | 9816       | 3.38                   |
| 216 h | 4647         | 4912                   | 9559       | 4.22                   | 5252             | 4912                   | 1016       | 2.99                   |



**Figure 15** - Parameter A - “Set up” lateral factor - Maximum Envelope - PC01.



**Figure 16** - Parameter A - “Set up” lateral - 120 cm - PC01.

### 5.5. Coyle-Reese method using the last blow (120 cm) 216 h

The pile was divided into 8 segments, a number higher than the subsoil layers, described above. The unit skin friction values  $f_s$  along the SFL Clay layer varied along depth, in agreement with SPT increasing from 2 to 4. Therefore, this layer was divided into two parts of 10 m each, as shown in Table 10.

The toe quake is equal to 1.76 mm, the mobilized toe resistance is 4912 kN and the elastic modulus of the pile material is equal to 207 GPa. Note, in advance, that the Static Load Test (SLT) was carried out with a pile length of 36.14 m (see Table 6). Regarding Fig. 17 (a), the pile length was taken as  $36.14 + 2.84 \approx 39$  m, in which 2.84 m is the distance between the PDA sensors and the soil surface. This length was used to calculate the pile elastic shortening on the Coyle-Reese method whose result shows an excellent correlation with the simulated CAPWAP curve, both associated to the last blow (120 cm) and a “set up” period of 216 h. The comparison between the Coyle-Reese curve with the Static Load Test (SLT) can be made through Fig. 17 (b). In this case, the pile length was taken equal to 36.14 m (see Table 6) and the small variation between both curves occurs mainly due to the “set up” period in which each test was performed, with a difference of 90 days.

### 5.6. Coyle-Reese method using the Maximum Envelope of Lateral Resistance - 216 h

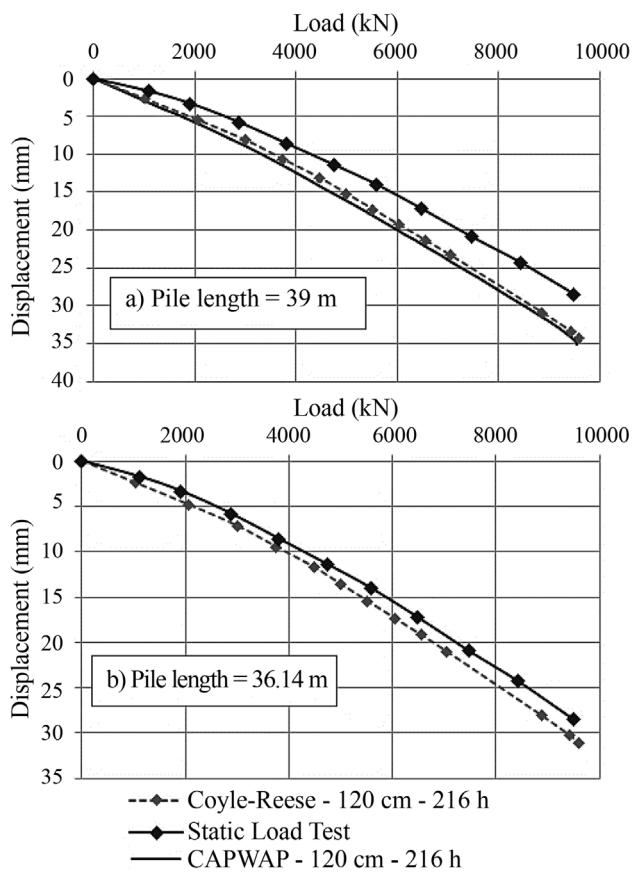
The data of the load transfer functions given by the Maximum Envelope are shown in Table 11 and the resulting curve of the Coyle-Reese method is shown in Fig. 18.

Figure 18 shows remarkable correlation between the curves simulated by Coyle-Reese method and provided by the Static Load Test (SLT). The total capacity, estimated at 10164 kN by the Coyle-Reese method is indicated by the vertical dashed line. This is exactly the same value calculated by the Maximum Envelope for the 216-h rest period.

As the “set up” time increases, the toe mobilized resistances decrease. Therefore, the simulated curve by CAPWAP (120 cm and 216 h) incorporated the lowest mobilization of toe resistance, indicated as 4912 kN in Table 8. In the context of the Maximum Envelope Method, stated above, a new simulated curve by the Coyle-Reese method was done and shown in Fig. 19 considering the highest mobilization of toe resistance of 5717 kN (Table 8) with a quake of 3.1 mm, both values calculated at the end of driving (EOD). The excellent correlation is maintained and,

**Table 10** - Input data for the Coyle-Reese Method - 120 cm - PC01.

| No. | Soil layer         | $\Delta H$ (m) | $f_{max}$ (kPa) | $y_n$ (mm) | $B = f_{max}/y_n$ (kPa/mm) |
|-----|--------------------|----------------|-----------------|------------|----------------------------|
| 1   | Sand earthwork     | 1.3            | 23.5            | 5.73       | 4.1                        |
| 2   | Clayey sand        | 2              | 26.4            | 5.73       | 4.6                        |
| 3   | Organic Clay (SFL) | 10             | 18.3            | 5.73       | 3.2                        |
| 4   | Organic Clay (SFL) | 10             | 37.3            | 5.73       | 6.5                        |
| 5   | Clayey sand (SFL)  | 4              | 52.6            | 5.10       | 10.3                       |
| 6   | Coarse sand        | 2              | 85.5            | 3.90       | 21.9                       |
| 7   | Silty sand         | 2              | 147.0           | 3.00       | 49.0                       |
| 8   | Sandy silt         | 2              | 150.2           | 2.10       | 71.5                       |



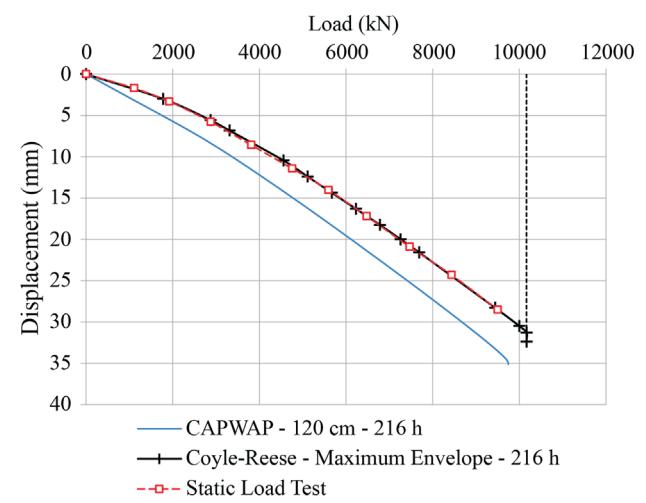
**Figure 17** - Simulated load set curves vs. Static Load Test -PC01.

furthermore, the total capacity increased from 10164 kN to 10969 kN, as indicated by the vertical dashed line.

#### 5.7. Summary of the results on static resistances - PC01

Table 12 summarizes the results obtained for the second case, related to mobilized static resistances. Based on these results, it is concluded that lateral resistance estimated by the Maximum Envelope associated with the Coyle-Reese Method is higher than that given solely by the CAPWAP of the last blow; the difference is  $5252 - 4647 = 605$  kN. Moreover, as shown above, it was possi-

ble to obtain a simulation of the load-settlement curve of



**Figure 18** - Simulated load set curves vs. Static Load Test - PC01.

the pile top that approaches very well the Static Load Test (SLT) curve.

## 6. Conclusions

The application of CAPWAP only to the last blow of a dynamic increasing energy test underestimated the maximum mobilized capacity and the resistance distribution along the shaft, particularly in soils with high sensitivity, as was shown in the two studied cases. Initial blows can change the properties of the soil. This behavior is clearly seen in the curve of the lateral skin friction vs. displacement of the SFL Clay layer, shown in the first case study. The Maximum Envelope of Lateral Resistance made it possible to recover the lateral skin friction information lost in blows prior to that with maximum applied energy.

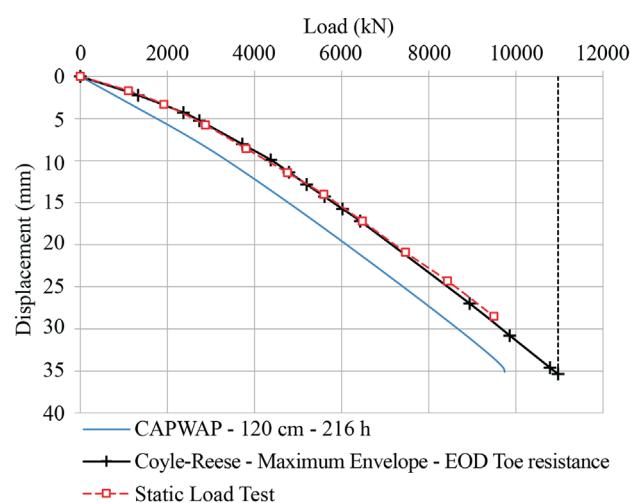
Compared to the load-settlement curve obtained in the Static Load Test (SLT), a set of simulated CAPWAP static curves involving all blows in the first case, like a cyclic test, revealed an equal to or better correlation than the

**Table 11** - Input data for the Coyle-Reese method - Maximum Envelope - PC01

| No. | Soil layer         | $\Delta H$ (m) | $f_{max}$ (kPa) | $y_n$ (mm) | $B=f_{max}/y_n$ (kPa/mm) |
|-----|--------------------|----------------|-----------------|------------|--------------------------|
| 1   | Sand earthwork     | 2              | 25.9            | 5.10       | 5.1                      |
| 2   | Clayey sand        | 2              | 27.3            | 5.10       | 5.3                      |
| 3   | Organic Clay (SFL) | 10             | 29.5            | 2.68       | 11.0                     |
| 4   | Organic Clay (SFL) | 10             | 42.2            | 4.65       | 9.1                      |
| 5   | Clayey sand (SFL)  | 4              | 53.4            | 4.36       | 12.3                     |
| 6   | Coarse sand        | 2              | 105.3           | 3.07       | 34.3                     |
| 7   | Silty sand         | 2              | 147.0           | 3.01       | 48.8                     |
| 8   | Sandy silt         | 2              | 150.2           | 2.09       | 71.9                     |

**Table 12** - Summary of the results - PC01.

| Test / Method                            | Static resistance (kN) |      |       |
|--|------------------------|------|-------|
|  | Lateral                | Toe  | Total |
| Static Load Test (SLT)                   | -                      | -    | 9497  |
| CAPWAP - 120 cm - 216 h                  | 4647                   | 4912 | 9559  |
| Coyle-Reese -120 cm - 216 h              | 4684                   | 4912 | 9596  |
| Maximum envelope - 216 h                 | 5252                   | 4912 | 10164 |
| Coyle-Reese - Maximum envelope - 216 h   | 5252                   | 4912 | 10164 |
| Maximum Envelope - EOD Toe Resistance    | 5252                   | 5717 | 10969 |
| Coyle-Reese - Maximum envelope - EOD Toe | 5252                   | 5717 | 10969 |

**Figure 19** - Simulated load set curves vs. Static Load Test - PC01.

single CAPWAP simulated curve of the last blow, with the greater hammer drop height.

Moreover, the maximum lateral friction values calculated by the Maximum Envelope Method allowed the estimation of the load transfer functions for each soil layer, leading to successful applications of the Coyle-Reese Method. The load-set curves in the 2 studied cases correlated very well with the Static Load Tests (SLT). Such correlations were better in comparison with the simulated CAPWAP static analysis for only one signal, with the maximum applied energy.

The Maximum Envelope of Lateral Resistance performed in several rest periods allowed an assessment of the skin friction development over time for the second studied case. It was possible to calculate the lateral and total “set ups”, particularly for the SFL Clay layer. The parameter A of Bullock *et al.* was figured out, allowing the forecast of skin friction increases on long term for the SFL Clay of Santos Coastal Plain (“Baixada Santista”).

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### List of symbols

|   |   |
|---|---|
| A: Bullock's constant, dependent on soil type               | $q_{tu}$ : Unloading toe quake                  |
| B: Coyle and Reese's elastic slope                          | $q_u$ : Unloading quake                         |
| DIET: Dynamic Increasing Energy Test                        | $R_{lt}$ : Reload level                         |
| $f_{max}$ : Coyle and Reese's maximum element skin friction | $R_{nu}$ : Negative ultimate resistance level   |
| $f_s$ : CAPWAP's element skin friction                      | $R_{st}$ : Toe static resistance                |
| Q: Capacity, dependent on time                              | $R_{ut}$ : Maximum pile toe element resistance  |
| $Q_p$ : Coyle and Reese's toe resistance                    | SLT: Static Load Test                           |
| $q$ : Toe quake   | $t_g$ : Resistance Toe Gap                      |
|   | $U_n$ : Unloading multiplier                    |
|   | $u_{px}$ : Maximum element displacement         |
|   | $u_t$ : Maximum pile toe displacement           |
|   | $y_n$ : Coyle and Reese's element displacement  |
|   | $y_t$ : Coyle and Reese's pile toe displacement |