# Unexpected behavior of long steel H piles in Santos City, Brazil

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ABSTRACT
The paper deals with an unexpected behavior of long steel H piles used as foundations of tall buildings in Santos City. The piles were driven through 10 to 12m of a medium to compact sand overlaying up to 50 m of alternated layers of soft to medium clays plus sands. Four piles were submitted to static vertical loading tests; two of them were instrumented. It is shown that: a) the piles behaved as floating piles; b) the unit shaft resistances reached their maximum values with movements of 3 to 8 mm, except in the upper sand layer, that required more than 40 mm; c) this upper layer exerted a pressure on top of the underlain soft clay, drastically reducing its unit shaft resistance; and d) the piles behaved as piled rafts. Based on a mathematical model, it is shown how to estimate the total shaft resistance in load tests without instrumentation.

RÉSUMÉ
Le travail traite un comportement inattendu des pieux d'acier de grande longuer, enfoncées à travers 10 à 12m dans une couche du sable compact superposé jusqu'à 50 m de couches alternées d'argiles molles à moyennes et sables. Quatre pieux ont été soumis à des essais de chargement; deux pieux ont etés instrumentés. Le travail montre que: a) les pieux se comportaient comme flottants; b) les frottements lateraux unitaires atteindrent leurs valeurs maximales avec des déplacements de 3 à 8 mm, sauf dans la couche de sable supérieure, qui exigeait plus de 40 mm; c) cette couche supérieure a exercé une pression sur le sommet de l'argile molle, réduisant considérablement son frottement lateral; et d) les pieux se comportaient comme fondations mixtes semelle-pieux. S'appuyant sur un modèle mathématique, il est montré comment estimer le frottement lateral total en essais de chargement sans instrumentation.

## 1 INTRODUCTION

The City of Santos, located in the Southeastern Brazilian coast, with more than 600,000 inhabitants, has the biggest harbor area of Latin America. In the 1940's up to the 1970's a booming tourist industry led to the construction of tall buildings along the beach shore, up to 18 floors, supported by shallow foundations built on a 10 to 12m layer of medium to compact sand overlaying up to 50 m of soft to medium clays plus sand layers.

The difficulties to drive piles through the upper sand layer and the costs involved restricted severely their use for many years. Recently long steel H-piles, 50 m length, were driven to support tall buildings, with 20 to 24 floors. Their relatively small cross-sectional areas combined with their high strengths made penetration easier through the upper dense layer. Welding four segments of decreasing cross sectional areas gave to each pile a slight step-tapered form, reducing costs.

The paper deals with two of such piles, submitted to static vertical loading tests and instrumented with strain gages along their lengths. Moreover, a mathematical model, called Two Straight Lines Method, developed originally for rigid or short piles, even with shaft enlargements or bulbs, was extended to piled rafts for both, rigid or compressible piles, and floating or end bearing piles. An application of this model is made to the long steel H-piles of Santos.

## 2 THE SANTOS' SUBSOIL

Many geological evidences show that the sedimentary clays of the Santos Coastal Plain ("Baixada Santista") were formed at least during two Quaternary depositional cycles, with an intermediate erosive process (Suguio and Martin 1981). This gave origin to the Pleistocene Clays and the Holocene Clays. The former ones, also called Transitional Clays (AT), deposited 100,000 to 120,000 years BP (Before Present), are medium to stiff clays. The latter ones are usually very soft to soft clays and include: a) the SFL clays (from Sediments-Fluvial-Lagoon-Bay), originated since 10,000 years BP by sedimentation where the Pleistocene sediments had been eroded; and b) the mangrove sediments, that are still forming.

The soft SFL clays of Santos City were deposited more than 7.000 years BP probably over AT sediments (Fig. 1). They are overlaid by a 8-12 m thick sand deposit, originated from the displacement of barrier islands, developed during periods of land submergence. These barrier-islands shaped lagoons on their backside, that lasted partially isolated for relatively long periods of almost stable sea-level. With the subsequent rapid lowering of the sea-level (periods of land emersion), the barrier-islands displaced toward the continent isolating completely the lagoons from the open sea and causing their desiccation. Eolic deposits were always present in the area. The resulting erratic over-consolidation of the soft clays is due to negative sea-level oscillations or dune action. This fact explains some anomalous behavior of tall buildings rested on shallow foundations, as: a) the scattering in the magnitude and rate of primary settlements and in the secondary consolidation rate; b) the greater settlement in the least loaded corner; and c) the inclination of isolated buildings, without the influence of nearby edifices (Massad, 2009-a and 2010).

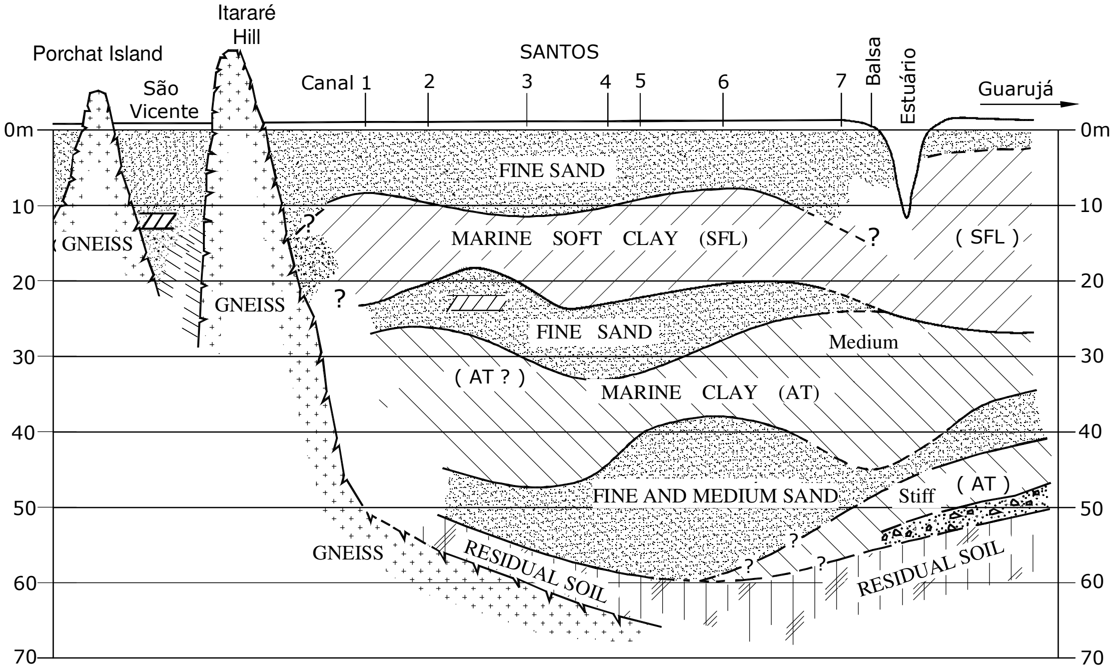

Fig. 1: Geological Section. Santos and São Vicente Shoreline (Adapted from Teixeira 1994)

## 3 EVIDENCES OF A "PILED-RAFT EFFECT" IN LONG PILES

Due to these anomalous behaviors the interest to use deep foundation increased. Falconi and Perez (2008-a) reported the use of long steel H-piles to support tall buildings in Santos City. Four of such piles (see Table 1) were submitted to static vertical loading tests.

Two piles, of buildings 6 and 8, were instrumented with strain gages installed along their lengths. Table 2 gives details of these piles. Only these piles will be analyzed in this paper. For more information see Falconi and Perez (2008-b) and Massad (2009-b).

Table 1: Data on buildings and piles

| Building | N | $h_c$<br>m | $S_{max}/S_{min}$<br>$cm^2$ | $P_w$<br>kN | s<br>mm | ρ<br>mm |
|---|---|---|---|---|---|---|
| 6 | 17 | 49.0 | 124/100 | 2050 | 69 | 18 |
| 7 | 16 | 47.5 | 136/100 | 2310 | 50 | 18 |
| 8 | 20 | 51.0 | 136/100 | 2320 | 35 | 15 |
| 9 | 23 | 51.0 | 109/102 | 1650 | 45 | 20 |

Legend: see appended list of symbols

Table 2: Data on the instrumented steel H piles

| Building | Steel Segments | Δh<br>m | S<br>$cm^2$ | p<br>m | $K_r$<br>kN/mm |
|---|---|---|---|---|---|
| 6 | HP 310X97 | 13 | 124 | 1.226 | 48.0 |
|  | HP 310X93 | 12 | 120 | 1.222 |  |
|  | HP 310X79 | 12 | 100 | 1.210 |  |
|  | HP 310X79 | 12 | 100 | 1.210 |  |
| 8 | W 310X107 | 15 | 136 | 1.234 | 49.4 |
|  | HP 310X97 | 12 | 124 | 1.226 |  |
|  | HP 310X93 | 12 | 120 | 1.222 |  |
|  | HP 310X79 | 12 | 100 | 1.210 |  |

Legend: see appended list of symbols

Table 3: Soil parameters– Building 8, Santos City

| z (m) | Soil layer | SPT | $f_{max}$<br>(kPa) | $y_1$<br>(mm) |
|---|---|---|---|---|
| 1 to 12 | Upper sand | 10 to 30 | 60 | 36 |
| 12 to 17 | SFL clay | 1 to 2 | 20 | 4 |
| 17 to 22 | SFL sand (?) | 15 to 50 | 20 | 4 |
| 22 to 33 | SFL clay | 2 to 5 | 25 | 5 |
| 33 to 43 | AT | 4 to 5 | 65 | 4 |
| 43 to 50 | Pleistoc. Sediment | 5 to 22 | 130 | 3 |
| >50 | Residual soil | ~15 | - | - |

Legend: see appended list of symbols

### 3.1 Pile of Building 8

The instrumented pile of Building 8 gave the most complete set of information. Table 3 shows schematically the subsoil profile at the site, with SPT data.

The strain measurements at various depths allow preparing the plots of Figs. 2, 3, 4 and 5.

Fig. 2 has a simple interpretation. Suppose that for a load $P'_o$, applied on pile top, the total lateral resistance reached its maximum value $A_{lr}^z$ at depth *z.* Assume also that at this depth the measured strain is $\varepsilon_z$. Then*:*

$$P'_o = A_{lr}^z + E \cdot S \cdot \varepsilon \quad with \quad \varepsilon = \varepsilon_z \qquad [1]$$

This means that at depth $z$ the plot of $P_o=f(E.S.\varepsilon)$ is a straight line for strains $\varepsilon$ greater than $\varepsilon_z$. This happened at all depths, as shown in Fig. 2.

From these considerations, it follows that a lower limit of $dP'_o/d\varepsilon$ is given by:

$$\left(\frac{dP'_o}{d\varepsilon}\right)_{lim} = E\cdot S \qquad [2]$$

Fig. 3 shows that $E.S$ varies from 2.1 to 2.6GN, consistent with the cross sectional areas indicated on Table 2 for building 8.

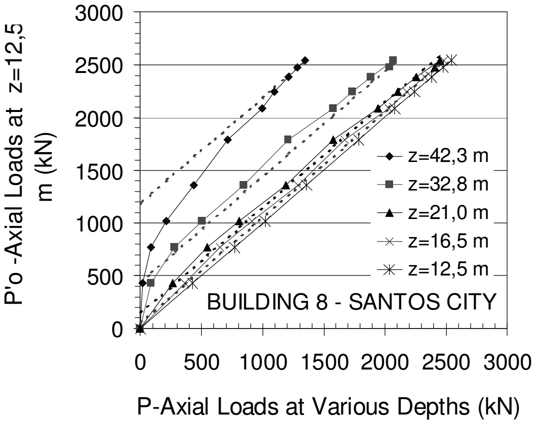

Fig. 2. P'$_o$ versus P=E.S.$\varepsilon$ (see appended list of symbols)

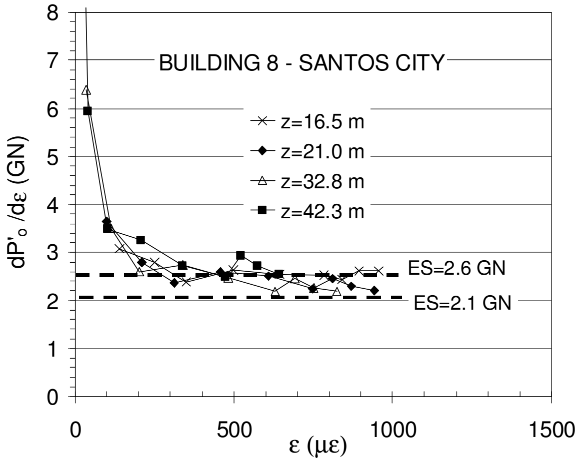

Figure 3. Values of E.S

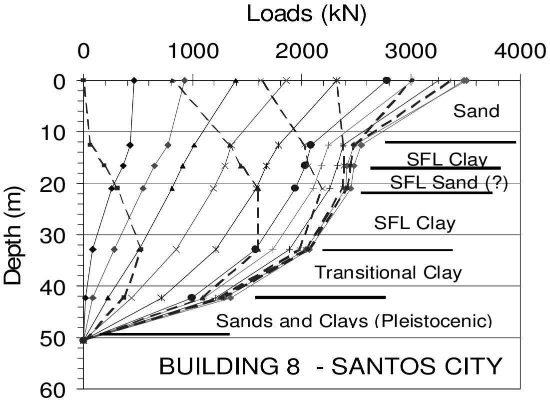

Figure 4. Load transfer diagram

The following conclusions may be drawn: a) the pile behaved as a floating pile (Fig. 4); b) the total shaft resistance equals 3,510kN (Fig. 4); c) the unit shaft resistances reached rapidly their maximum values in all levels, except in the upper sand layer (Fig. 5); in this context, compare $y_1$ values of the layers in Table 3; and d) this upper layer exerted a pressure on top of the underlain soft SFL clay, drastically reducing its unit shaft resistance (Fig. 5).

The last conclusion suggests the existence of a bulb (an enlargement) in the upper sand layer; or, in other word, the pile behaved as a piled raft. The base of the raft would be positioned at the interface between the upper sand and the underlying soft SFL clay, at depth 12.5m. This conjecture justifies the use in Fig. 2 of $P'_o$, the axial load at depth 12.5m.

The values of the maximum unit shaft resistances of each soil layer are shown in Table 3. These figures are in agreement with measurements in other sites of Baixada Santista (Massad 2.009-a and 2.009-b).

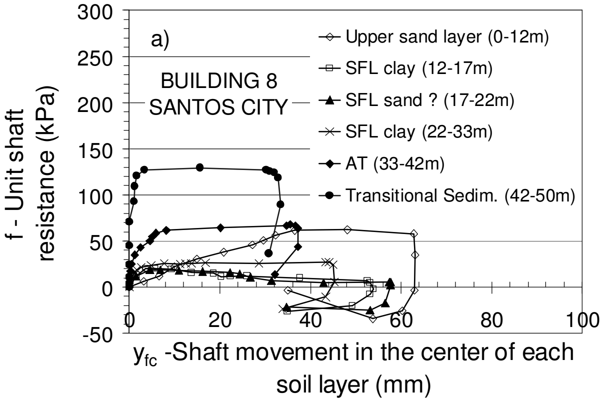

Figure 5. Load transfer functions

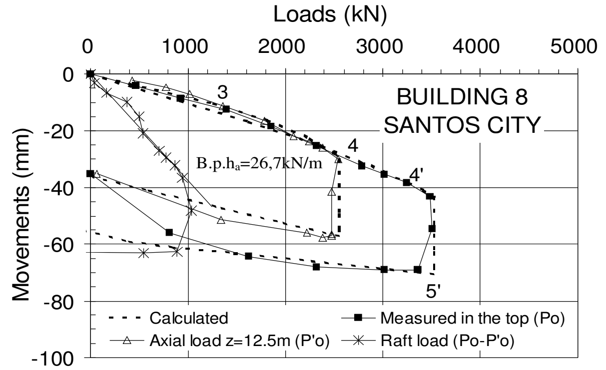

Figure 6. Loads-movements (*yo, y'o* and *y$_{fc}$*)

Fig. 6 shows the load-movement curves related to: a) the top ($P_o$ vs. $y_o$); b) the raft (($P_o$-$P'_o$) vs $y_{fca}$); and c) the pile of the piled raft ($P'_o$ vs. $y'_o$). Fig. 7 is analogous to Fig. 6, but all loads are referred to the top movement ($y_o$). As $P'_o$ is equal to the total shaft resistance between 12.5 and 51m (pile toe), it can be concluded that the unit shaft resistances reached their maximum values simultaneously either in the upper sand layer and the lower layers, due to the relatively high pile compressibility.

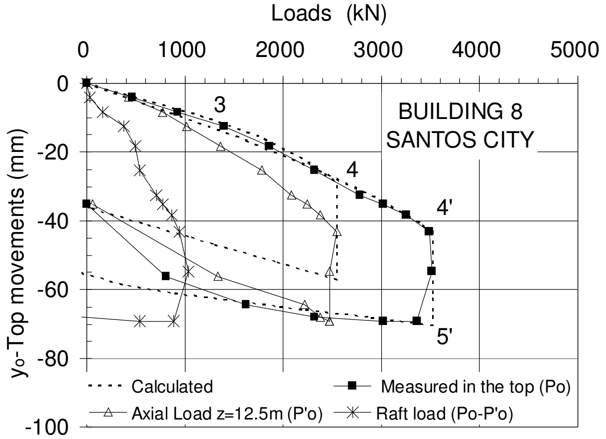

Figure 7. Loads-top movements ($y_o$)

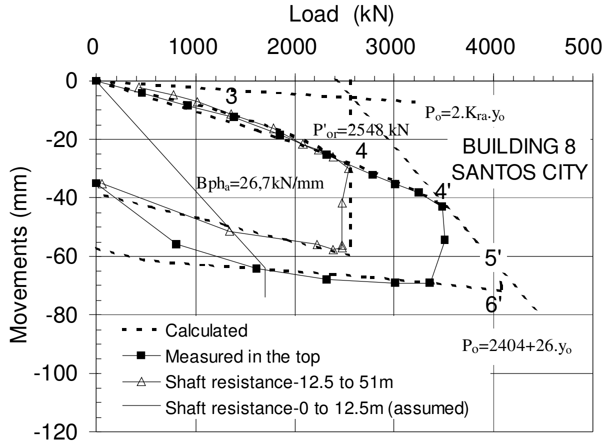

Figure 8. Simulation assuming a higher shaft resistance in the upper sand layer

Based on a mathematical model – the Two Straight Lines Method - mentioned above and developed by Massad (2009-b), Fig. 8 was prepared. It is similar to Fig. 6 but assuming that the unit shaft resistance of the upper sand layer reached its maximum value for $y_{fca}$>60mm.

In this case the curve $P_o$ vs. $y_o$ would extend to point 6', passing through points 4' (ultimate shaft resistance of the pile of the "fictitious piled raft" was reached) and 5' (ultimate "raft" load was reached). The straight line 4'-5' represents the remaining shaft resistance offered by the upper sand layer, or the equivalent load transmitted by the "fictitious raft" alone. The equation of this line is (Massad 2009-b):

$$P_o = d_1 + d_2 \cdot y_o \qquad [3]$$

The constants $d_1$ and $d_2$ are computed using the following relations:

$$\frac{1}{d_2} = \frac{1}{B.p.h_a} + \frac{1}{4K_{ra}} \qquad [4]$$

$$P'_{or} = \frac{d_1}{1 - d_2/(2K_{ra})} \qquad [5]$$

where: a) $B.p.h_a$ is the "fictitious raft" stiffness; b) $K_{ra}$ is the stiffness of the H-Pile segment, embedded in the upper sand layer; and c) $P'_{or}$ is the ultimate total load acting on top of the fictitious pile of the "piled raft". If line 4'-5' is known, than Eq. 5 or the simple graphical construction of Fig. 8 allow the estimation of $P'_{or}$.

### 3.2 Pile of Building 6

The H-Pile of Building 6 was also instrumented but with a restriction in number and positions of the strain gages (see Fig. 9). Nevertheless, the strain measurements leaded to the following conclusions (Massad 2009-b): a) the pile behaved as a floating pile; b) the total shaft resistance was greater than 3,309 kN and the ultimate toe load was roughly 190 kN; c) the unit shaft resistances reached rapidly their maximum values in all levels, except in the 3 upper layers; and d) after unloading, a residual load of 60 kN was locked in the toe.

The piled raft effect is evidenced in the graphical construction (Massad 2009-b) of Fig. 10. It can be seen that the ultimate total load (*P’or*) acting on top of the pile of the “fictitious piled raft” is of the order of 2,583 kN and, consequently, the total shaft resistance in the upper sand layer alone is greater than 3,309-2,583=726 kN.

This graphical construction may be used to estimate the total shaft resistance in load tests without instrumentation.

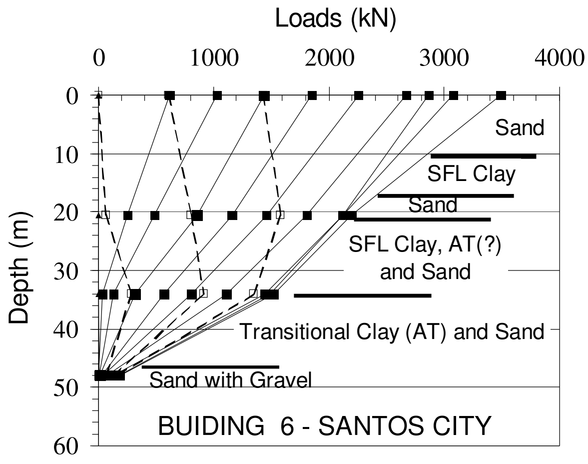

Figure 9. Load transfer diagram

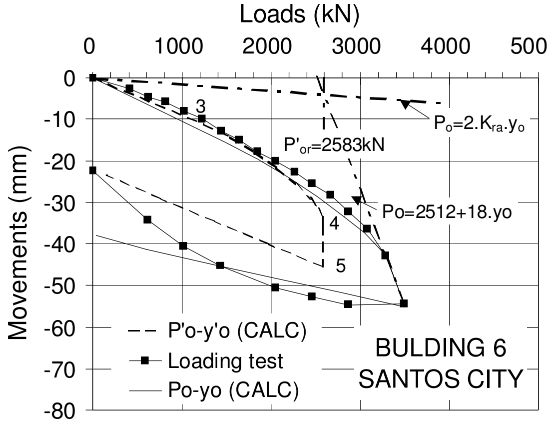

Figure 10. Loads-movements

## 4 CONCLUSIONS

The paper presented an explanation for an unexpected behavior of long steel piles in Santos City.

The unit shaft resistances reached their maximum values after shaft movements of a few mm, except for the upper sand layer, that required tens of mm. This fact suggested a behavior like a pile toe or an enlargement (bulb) in the upper bearing sand layer. Or, in other word, the pile behaved as a piled raft.

This effect brought about a reduction in the unit shaft resistance of the soft SFL clay, bellow the upper sand layer. If the resistance of this upper layer is very high, negative skin friction could develop in the soft clay.

Finally, it is suggested that long floating piles in Santos City should consider this piled raft effect and its consequences in the design. For instance, the working load shall be limited by the total shaft resistance bellow the upper medium to compact sand layer, minimizing the pressure on top of the soft SFL clay.

## ACKNOWLEDGEMENTS

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## LIST OF SYMBOLS

| | |
|---|---|
| $A_{lr}^{z}$: | Total Maximum Lateral (Shaft) Resistance up to depth z |
| AT: | Transitional Clay (Pleistocenic) |
| B: | “Spring constant” of the soil along the pile shaft or Parameter of the First Cambefort’s Law |
| BP: | Before Present |
| $d_1$; $d_2$: | Constants |
| E: | Young's Modulus of Pile Material |
| f: | Unit Shaft Resistance |
| $f_{max}$: | Ultimate Unit Shaft Resistance |
| $h_a$, | Pile Length in the Upper Sand Layer |
| $h_c$: | Pile Embedment |
| $K_r$: | Average Stiffness of an H-Pile |
| $K_{ra}$: | Stiffness of the pile segment, in the upper sand layer |
| N: | Number of Building Floors |
| p: | Perimeter of the H-Piles (4 sides) |
| P: | Axial Load along Pile Length |
| $P_o$: | Pile Top Load |
| $P'_o$: | Top Load of the “Fictitious Pile” |
| $P'_{or}$: | Ultimate Value of $P'_o$ |
| $P_w$: | Working Load |
| s: | Pile Set |
| S: | Cross Sectional Area of the Pile |
| SFL: | Sediments-Fluvial-Lagoon-Bay |
| $S_{max}$;$S_{minx:}$ | Maximum and Minimum values of S |
| $y_o$: | Movement of Pile Top |
| $y'_o$: | Movement of the Pile Top of the “Fictitious Pile” of the Piled Raft |
| $y_1$: | “Shaft quake” or Parameter of the First |

Cambefort’s Law
$y_f$: Movement of a Point Along the Shaft
$y_{fc}$: Value of $y_f$ in the Center of a Soil Layer
$y_{fca}$: Value of $y_{fc}$ in the Center of upper sand layer
z: Depth
$\Delta h$: Length of of an H-Pile segment
$\varepsilon$: Strain
$\rho$: Pile Rebound

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