Effect of Soil Plugging on Axial Capacity of Open-Ended Pipe Piles in Sands

Effet de formation d'un bouchon sur la capacité d'un pieu ouvert dans le sable

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ABSTRACT: A degree of soil plugging during pile driving affects the ultimate capacity of open-ended pipe piles. A few researchers have attempted to quantify the effect of soil plugging on pile capacity by introducing PLR (plug length ratio), ratio of length of soil plug to pile penetration depth. However, the majority of these attempts were based on model pile tests conducted in the laboratory that may not be directly applicable to field conditions due to scale effects. In this paper, we measured plug lengths at final penetration depths for 1,355 open-ended driven pipe piles with pile diameters ranging between 406 mm and 914 mm. These piles were driven mainly in dense to very dense sandy soils. The pile penetration depths ranged between about 10 m and 30 m. Our analyses indicated that the PLR values increased with the increase in pile diameter in the given soil conditions. We performed PDA (pile driving analyzer) tests on 99 piles and estimated skin friction and end bearing values of the 99 piles from CAPWAP (CAse Pile Wave Analysis Program) analyses. The results from our analysis indicated that unit skin friction and unit end bearing values increased with decreasing PLR. We suggested new design equations for estimation of skin friction factor β and end bearing factor N_q for piles driven in dense to very dense sands.

KEYWORDS: open-ended steel pipe piles; plug length ratio (PLR); pile capacities; pile design.

1 INTRODUCTION

1.1 *Soil plugging*

When an open-ended pipe pile is driven into the ground, it is very likely that the soil enters inside of the pile in the initial stage of pile driving at very shallow depths. If pile penetration depth is equal to the soil plug length, this behavior is typically referred to as "fully coring" or "unplugging" behavior. As the pile is driven deeper into the soil, the soil friction on the inside of the pile wall increases until a "soil plug" is formed, which may prevent or partially restrict additional soil from entering the inside of the pipe. This behavior is referred to as "plugging", and the length of soil plug is less than the pile penetration depth.

Even though soil plugging behavior of open-ended pipe piles has been a recognized issue (Kishida and Isemoto 1977; Klos and Tejchman 1977), the efforts to quantify the degree of soil plugging have been very rare. The two most widely used indicators of soil plugging are plug length ratio (PLR) and incremental filling ratio (IFR), respectively, defined as

$$PLR = L / D \quad (1)$$

$$IFR = dL / dD \quad (2)$$

where D = pile penetration depth; L = length of soil plug; dD = increment of pile penetration depth; and dL = increment of soil plug length corresponding to an increment of pile penetration depth dD (see Fig. 1). By definition, IFR is a first derivative of PLR, meaning that IFR is a slope of curve of plug length versus pile penetration depth plot. As shown in Fig. 1, in the case of a fully coring mode, PLR and IFR must be equal to 1.

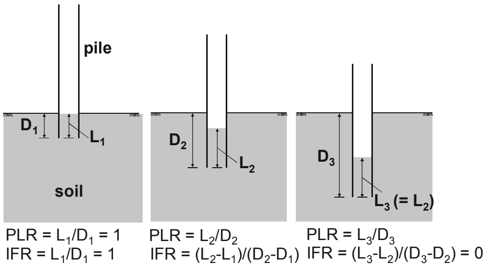

Figure 1. Soil plugging mode.

In the case of fully plugging mode, however, IFR at final penetration must be equal to zero because additional soils do not enter inside of the pile after the previous penetration, but PLR is not necessarily zero at that depth. Typically, open-ended piles for onshore applications are driven in partially plugging mode in sandy soils (Paikowsky et al. 1989; Paik and Salgado 2003).

PLR is a good indicator of degree of overall soil plugging, and researchers proposed to use PLR for estimation of limit unit skin friction of open-ended pipe piles (Paik and Salgado 2003). The better indicator of soil plugging on estimation of end bearing values may be IFR, as it can represent the condition of soil plugging at the final penetration depth from final pile driving. Paik and Salgado (2003) proposed an equation, derived from model pile tests in calibration chamber, for estimating the unit end bearing value in sandy soils using IFR. They showed that the unit end bearing normalized to horizontal effective stress increases with increasing relative density and decreasing IFR.

Lehane et al. (2005) suggested using FFR (final filling ratio), defined as a value of IFR averaged over a distance of 3 pile diameters above the pile tip, to relate the unit end bearing value with the cone penetration resistance in sandy soil. In the field, it is easier to measure PLR than IFR. Therefore, Paik and Salgado (2003) proposed an equation to estimate IFR from the PLR, when only the PLR is measured in the field. This equation was derived from the results of model piles driven in sands of various confining stress and relative density to a depth of 760 mm. The model pile had an outside diameter of 42.7 mm, inside diameter of 36.5 mm, and length of 908 mm. Even though the ratio of pile length to pile diameter of the model pile was close to that of the piles driven in the field (in fact, close to a the lower bound of ratio of length to diameter of piles typically driven in field), the ratio of pile diameter to soil particle size of the model pile test was far from that of the field condition. Therefore, the relationship between PLR and IFR suggested by Paik and Salgado (2003) may not be applicable to field condition. Furthermore, as Lehane and Gavin (2004) pointed out and Paik and Salgado (2004) agreed in a separate discussion, the correlation between PLR and IFR are not applicable near the interface of two sand layers with very different relative densities, as the relation was developed based on the calibration chamber test data where soil conditions are relatively homogeneous. In reality, it is not easy to measure even PLR for routine piling work. For this reason, Lehane et al. (2005) proposed a formula for estimating IFR_{avg}, averaged over 20 pile diameters of penetration, as a function of the pile internal diameter as follows:

$$IFR_{avg} = PLR = \min\left[1, (B_i/1.5)^{0.2}\right] \quad (3)$$

where B_i = pile inside diameters in meters. It should be noted that the average of the IFR measured with the same penetration increments over the entire pile length is equal to the PLR.

Yu and Yang (2012) determined that the ratio of unit end bearing of soil plug to tip resistance from the cone penetrometer tests (CPT) depends on PLR. They collected PLR data from literature and suggested the following equation to estimate PLR from internal pile diameter:

$$PLR = \min\left[1, B_i^{0.15}\right] \quad (4)$$

1.2 *Pile design*

The total axial capacity Q_t of open-ended steel pipe pile is the sum of the limit skin friction Q_s and the ultimate end bearing Q_b:

$$Q_t = Q_s + Q_b = \sum q_{si} A_{si} + q_b A_b \quad (5)$$

where q_{si} = limit unit skin friction for soil layer i; q_b = ultimate unit end bearing; A_{si} = pile shaft area interfacing with soil layer i; and A_b = area of pile base. There exist many methods to estimate q_s and q_b. Among others, the method proposed by American Petroleum Institute (API) is one of the most widely methods used for design of on- and off-shore foundations in USA.

According to the API (2007), the unit skin friction in sandy soils can be derived from the normal effective stress acting on the pile shaft and the frictional properties between the pile and soil interface as:

$$q_s = K\sigma_v' \tan\delta \quad (6)$$

where K = coefficient of lateral earth pressure; σ_v' = vertical effective stress in the center of the soil layer; and δ = soil-pile interface friction angle. The K and δ are often incorporated together as shaft friction factor β, and Eq. (6) then becomes:

$$q_s = \beta\sigma_v' \quad (7)$$

According to the API (2007), β values vary between 0.37 and 0.56 for open-ended pipe piles driven in unplugged mode for medium dense to very dense sands. The API suggests increasing β by 25 percent for full-displacement piles such as open-ended pipe piles driven in fully plugged mode or for closed-ended pipe piles.

The unit end bearing for piles installed in sandy soils is given as:

$$q_b = N_q\sigma_v' \quad (8)$$

where σ_v' = vertical effective stress at the base of pile; N_q = end bearing factors ranging between 20 and 50, for medium dense to very dense sands.

2 SITE CONDITIONS AND PILE DRIVING

2.1 *General site conditions*

The project area is about 270-m-wide and 400-m-long. A total of 10 soil borings with Standard Penetration Tests (SPT) and 1 Cone Penetration Test (CPT) were performed within the area. The existing site grade at the time of exploration varied from about El. 354.5 m to about El. 359.5 m. At the time of pile driving, the finished grade was at about El. 356 m, with typical groundwater level at 6 m below the finished grade. The project area generally consists of dense silty sands (typically consisting of 60 % of sand, 33 % of fines, and 7% of gravel) from below the finished grade to a depth of about 6 m. The SPT N-values within this stratum generally ranged between 13 and 49 blows with an average of about 31 blows. Below this layer, dense to very dense sands (typically consisting of 89 % of sands and 11 % of fines) were encountered to a maximum depth of about 40 m. The SPT N-values within this stratum generally ranged between 41 and greater than 50 blows. CPT also shows similar soil conditions with average cone resistance q_t of 25 MPa to a depth of about 6 m, and 42 MPa thereafter.

2.2 *Pile driving and dynamic testing*

A total of about 3,000 steel pipe piles were driven at the project site. We measured plug lengths for about 1,355 piles. The pipe piles driven in the project area consist of 406 mm x 9.5 mm (pile outer diameter B_o x wall thickness t), 508 mm x 12.7 mm, 610 mm x 12.7 mm, 762 mm x 15.9 mm, and 914 mm x 19.1 mm open-ended steel pipe piles (corresponding to inner diameters of 387, 483, 585, 730, and 876 mm, respectively). APE D46-32 diesel hammer was used to drive the 406-, 508-, and 610-mm-diameter piles. APE D62-42 and APE D80-42 diesel hammers were used to drive the 762- and 914-mm-diameter piles, respectively.

We measured the hammer blow counts required for driving piles each 0.25-m interval to the final penetration depths. After completion of the pile driving, we measured the depth of the top of soil plug using a wire-connected weight lowered inside the pile and rested on top of soil plug. We then calculated the soil plug length from the pile penetration depth and stick-up length above the ground.

In order to estimate the pile capacity, dynamic load tests were performed on 99 piles using the PDA. The pile capacities were estimated based on signal matching analysis using CAPWAP.

3 EXPERIMENTAL RESULTS

3.1 *Soil plug length ratio*

As mentioned earlier, we measured the plug lengths of a total of 1,355 piles. The pile penetration depths ranged between about 10 m and 30 m. The lengths of the soil plugs at various final pile penetration depths are presented in Fig. 2(a) through 2(e). The dashed lines in these figures represent the fully coring state, and the solid line is a fitted line through the measured data. It is clear that the solid lines become closer to the dashed line as the pile diameter increases, indicating that the large diameter piles were driven in close to fully coring mode.

We performed histogram analysis of PLR values at final penetration depths. A summary of the statistical data of PLR is presented in Table 1.

Table 1. Summary of statistical data of PLR.

Outer Dia., mm	Total No. of Piles	Penetration Depth, m	Mean PLR	Standard Deviation	Most Frequent PLR Range
406	83	10.4 - 16.8	0.761	0.065	0.80 - 0.84
508	585	10.3 - 26.5	0.842	0.048	0.84 - 0.88
610	113	13.5 - 23	0.868	0.039	0.84 - 0.88
762	373	10.5 - 29.8	0.874	0.051	0.88 - 0.92
914	201	10.3 - 29.8	0.905	0.023	0.90 - 0.92

As seen in Table 1, the mean value of PLR increases from 0.76 for 406-mm-diameter pile to 0.91 for 914-mm-diameter pile. Data from 406-mm-diameter piles show the most scatter and 914-mm-diameter piles show the least scatter.

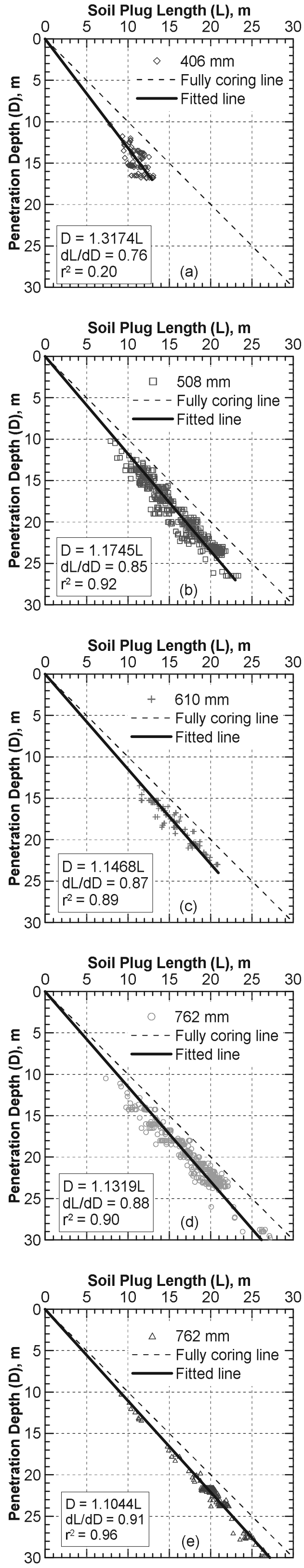

Figure 2. Pile Penetration Depth versus Soil Plug Depth for (a) 406-mm, (b) 508-mm, (c) 610-mm, (d) 762-mm, and (e) 914-mm-outer diameter piles.

Based on these observations, we propose the following equation to estimate the PLR as a function of pile inner diameter as follows:

$$PLR = (B_i / 1.4)^{0.19} \qquad (9)$$

where B_i = pile inner diameter in meters (0.387 m $\leq B_i \leq$ 0.876 m). Fig. 3 shows the measured PLR versus pile inner diameter B_i from this study. We also plotted the estimated PLRs from the equations suggested by Lehane et al. (2005) and Yu & Yang (2012). Predicted PLR values from Lehane et al. (2005) show good agreement with mean PLR values measured in this study, especially for large-diameter piles such as 762- and 914-mm-diameter piles. Perhaps this is because Lehane et al. derived Eq. (3) based on pile driving data of large-diameter off-shore piles. The equation proposed by Yu and Yang (2012) appears to form the envelope for upper bound values measured in this study.

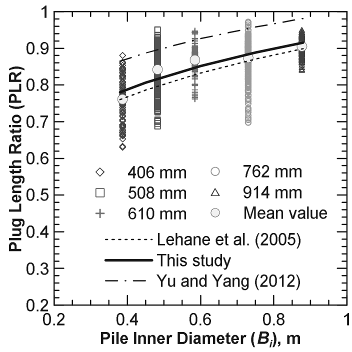

Figure 3. Pile inner diameter vs. measured PLR.

3.2 *Skin friction factor β*

In order to quantify the effect of the soil plugging on the unit skin friction, we back-calculated the shaft friction factor β in Eq. (7) from the CAPWAP capacities (see Safaqah et al. 2012 for detailed information on how skin friction and end bearing values were obtained from CAPWAP capacities). We first calculated the unit skin friction q_s by dividing skin friction values from CAPWAP analyses by outer area of pile-soil interface ($\pi B_o D$). We then divided q_s by the vertical effective stress σ_v' at the mid-depth of the pile length to obtain the average shaft friction factor β. Based on the back-calculated β and average PLR values of the PDA-tested piles with pile penetration depths ranging between about 10 m and 30 m, we established the following equation to estimate β from PLR and D:

$$\beta = (3.5 - 3.2PLR)e^{-0.023D} \qquad (10)$$

where PLR = plug length ratio (0.76 ≤ PLR ≤ 0.91) and D = penetration depth in meters (10 m ≤ D ≤ 30 m).

Fig. 4 shows the back-calculated β versus the mean PLR values of PDA-tested piles together with the predicted values from Eq. (10) with pile penetration depths of 10 and 30 m.

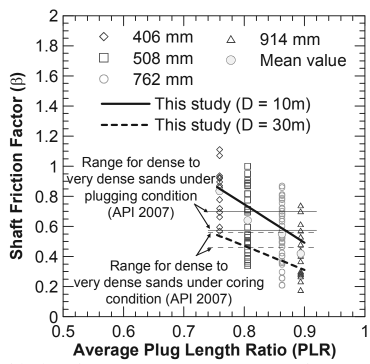

Figure 4. Skin friction factor β vs. average PLR of PDA-tested piles.

The mean β value decreases from 0.83 to 0.42 with PLR values increasing from 0.76 to 0.89. According to the API, β values are independent of pile diameter for open-ended pipe piles. However, Fig. 4 clearly shows that β is a function of PLR, which in turn is a function of the pile diameter. Furthermore, a mean value of β for 406-mm-diameter piles from this study is even larger than the value recommended by API for fully plugging condition. It also appears that as diameter increases, the mean values of β approaches to the values suggested by the API for coring condition.

3.3 *End bearing factor N_q*

The effect of soil plugging on unit end bearing was investigated using the end bearing factor N_q in Eq. (7). As mentioned previously, IFR is a better indicator for quantifying the effect of soil plugging on end bearing. However, IFR was not measured during pile driving because it is difficult to measure the change of the plug length over a certain interval in the massive piling work without interrupting the pile driving process. Additionally, Fig. 2 shows that the soil plug length generally increased linearly with the penetration depth, implying that IFR may not vary significantly during pile driving. Therefore, we used PLR to investigate the effect of the soil plugging on the unit end bearing. We first obtained the unit end bearing values q_b by dividing the tip resistances from the CAPWAP analyses by the gross cross-sectional area of the pile $(\pi B_o^2/4)$. We then divided q_b by the vertical effective stress σ_v' at a depth of pile tip to obtain the end bearing factor N_q. In reality, the operational area for the end bearing may be in between the steel and the gross areas for partially plugged pile. Therefore, the unit end bearing values obtained using the gross area may under-estimate the true unit end bearing. However, considering that it is very difficult to identify the actual operational tip area, it may be better to use the gross area to back-calculate N_q and use these values in conjunction with the gross area for pile design.

Fig. 5 shows back-calculated N_q versus average PLR values of PDA-tested piles.

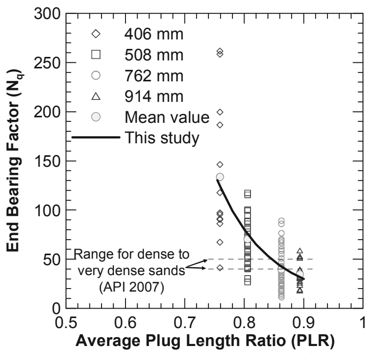

Figure 5. End bearing factor N_q vs. average PLR of PDA-tested piles.

We obtained the following equation for N_q by fitting for the mean values:

$$N_q = 12.3 PLR^{-8.4} \quad (11)$$

where PLR = plug length ratio ($0.76 \le PLR \le 0.91$). Eq. (11) indicates N_q decreases with increasing PLR. Mean N_q values vary from about 134 for 406-mm-diameter piles to 35 for 914-mm-diameter piles. API recommends using N_q = 40 for dense sand, and N_q = 50 for very dense sand regardless of pile diameter. Similar to the shaft resistance factor, API recommendations for end bearing factor seem to be appropriate for large piles such as 762-mm and 914-mm-diameter pile, but significantly underestimate that for 406-mm-diameter piles. Even though Eq. (11) indicates that N_q may increase drastically for very low values of PLR because of power relationship with PLR, in reality, the N_q values for the 406-mm-diameter piles obtained in this study may be close to the upper bound for pipe piles because these piles were most likely fully plugged at the end of pile driving. According to CGS (2006), the upper bound of N_q values for piles driven in dense to very dense sands is 120, which is indeed close to N_q values (=134) of 406-mm-diameter piles. In addition, the N_q value suggested by Paik and Salgado (2003) for fully plugged open-ended pipe piles (IFR = 0) in dense sand is $326K_0$., which yields 130 with K_0 = 0.4 and 163 with K_0 = 0.5.

It should be noted that Eqs. (10) and (11) are obtained from the piles driven in dense to very dense sands with PLR values ranging between 0.76 and 0.91. Therefore, these equations are not valid for loose or medium dense sands. We are performing similar study for the piles driven in medium dense sands. Eqs. (9) through (11) will be updated by including the effect of relative density of soils after the on-going study is completed.

4 SUMMARY AND CONCLUSION

In this study, we investigated the effect of the soil plugging on the capacity of open-ended steel pipe piles in dense to very dense sands. We measured the soil plug lengths at final penetration of 1,355 open-ended driven pipe piles with pile diameter ranging between 406 mm and 914mm. The pile penetration depths ranged between about 10 m and 30 m. The average PLR increased from 0.76 for 406-mm-diameter piles to 0.91 for 914-mm-diameter piles. Based on these observations, we suggested an equation from which PLR can be estimated based on pile inner diameter.

We estimated the skin friction and end bearing of the piles by performing PDA tests and performing CAPWAP analyses on 99 piles. These results indicated that the unit skin friction and unit end bearing values increased with decreasing PLR at the similar or equal relative density. We also compared the field pile capacities from CAPWAP analyses against the capacities estimated following API procedures. The results showed that the use of the API procedures might under-estimate the unit skin friction and unit end-bearing values for small diameter piles. We suggested new equations to estimate the skin friction factor β and end bearing factor N_q, based on PLR for dense to very dense sands.

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