# Time Effects on the Axial Compression Bearing Capacity of Piles Driven in Offshore Clays of Persian Gulf – A Case Study

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## Abstract

Nowadays, CPT based methods are vastly employed for predicting the bearing capacity of offshore piles. Previous experiences have shown that the pile capacity is time-dependent (setup and relaxation). Time effect on pile bearing capacity is extremely important which is missing in most CPT based prediction methods. Thus, the main objectives of this paper are: (1) comparing the pile capacity results of some popular CPT based methods with those obtained from Pile Dynamic Analyzer (PDA) and Case Pile Wave Analysis Program (CAPWAP) at End-Of-Drive (EOD) and Beginning-Of-Restrike (BOR) conditions periodically up to 9 months during pile installation; and (2) comparing the predictions of the most accurate CPT based methods to the Skov and Denver (1988) equation which has a semi-logarithmic time function form. For verification purposes, the critical focus of this study has been on employing the invaluable and very rare results of a test pile driven in offshore clays of South Pars field - Persian Gulf, Iran. The field results show that almost all CPT based methods estimate the pile capacity higher than those of EOD condition. However, they are generally close to the results of BOR condition as well as the Skov and Denver (1988) equation with 100-day time reference. In addition, comparing to the long-term predictions of CPT based methods, the set-up factor values proposed by NGI (2000) equation are the most precise ones against the CAPWAP results.

**Keywords: Offshore piles, Axial bearing capacity, CPT based methods, PDA test, Soil set-up.**

## 1. INTRODUCTION

The CPT based methods of determining offshore pile bearing capacity are identified as the most proper ones comparing to the other in-situ methods. CPT is accurate and fast and has significant similarities with pile. It provides reliable in-situ continuous sounding of subsurface soil condition and can also measures the excess pore water pressure immediately behind the cone ($U_2$) which is essential to correct the effective stresses in offshore environment. Comparing to laboratory experiments with soil sampling, minimum soil disturbance happens during CPT penetration. According to the mentioned CPT advantages, it can produce the meaningful pile bearing capacity results. Consequently, CPT or CPTu has been developed and used in many offshore projects to estimate the pile tip and shaft resistances.

However, geotechnical engineers often face to variation in pile bearing capacity with time particularly for those ones driven in fine-grained cohesive soils which is called "Time Effect" in the literature. It's well understood from laboratory and field tests that pile capacity can either increase (setup) or decrease (relaxation) with time. Setup is more common than relaxation and can occur in most soil types. However, it is predominant in fine-grained cohesive soils. During pile installation, the soil surrounding the pile experiences plastic deformations, remolding, and pore pressure changes. There is a reduction in effective stress when positive pore pressures are generated. As the pore pressures return to equilibrium, the effective stresses increase and consequently consolidation occurs around the pile shaft in cohesive soils resulting in strength gain. In low permeability cohesive soils, the time for pore pressure equilibrium can be several months. However, soil setup typically tends to begin almost immediately upon completion of initial pile installation. After the consolidationphase, the pile capacity increases due to soil aging effects. Commonly in offshore constructions, there are often several months of time elapses between installation of piles and the completion of the super-structure. During this period, piles would experience "time effects" on their capacities before the actual design load is applied. Thus, time is not associated with cyclic loading, loading rate and inertia. It is commonly believed that set-up is caused by two important factors:

1. *Dissipation of excess pore water pressures due to driving*. This leads to an increase of horizontal effective stresses acting against the pile shaft implying an increase of mobilized skin friction with time.

2. *Ageing*. Capacity increases with time due to changes in the characteristics of soil skeleton, changes in the pile-soil interaction and/or changes in the stress regime in the soil surrounding a driven pile. For piles in clay, thixotropy, cementation or bonding of clay particles with time also play a role.

Therefore, the pile bearing capacity calculation methods taking into account the time effects, shall be more favorable from the design point of view. In offshore environment, pile dynamic test using PDA equipment provides such a capability. The main advantage of PDA tests is the possibility of capacity measurement at various time steps, for example End-of-Drive (EOD) and at a certain time after the initial drive, so called Beginning of Restrike (BOR).

Herein, there are several determinant questions; - Whether the CPT predictions would more precisely correlate with End-Of-Drive (EOD) or Beginning of Restrike (BOR) conditions? Which CPT method is more consistent with PDA results in long-term condition? Whether the shaft resistance would more experiences the alternation after time elapses or the pile tip? Thus, the main objectives of this paper are to compare the results of CPT based prediction methods with the PDA records at both EOD and BOR conditions, obtained from the invaluable and very rare results of a test pile driven in offshore clays of South Pars field - Persian Gulf, Iran. Afterwards, the long-term predictions of CPT based methods are evaluated by driving the set-up factor values proposed by Skov and Denver (1988) [15], NGI (2000) [4] and Augustesen (2006) [19] equations.

## 2. CASE STUDY

A "Test Pile" was driven at the coordinates of 634 065.00 mE and 2 979 607.00 mN in South Pars field, Persian Gulf, southwest of Iran. It is an open-ended tubular steel pile with around 88 m length, 1.52 *m* diameter, and 50.88 *mm* wall thickness. Water depth at the pile location is nearly 79 *m*. Figure 1 shows the approximate location of test pile. The relevant soil and CPT data at corresponding location is given in Figure 2. The soil profiles have a general trend of increasing linearly with depth. However, the values fluctuate in some occasional non-cohesive granular lenses. In South Pars field, the clayey soil is very soft to soft at above 20 *m* depth, stiff at 20–70 *m* depth, and very stiff to hard beyond 70 *m* depth [1]. This layering pattern is dominant and no considerable variation is seen in the whole field. In order to measure the shaft, end and ultimate bearing capacities of the pile at field, PDA tests were carried out at EOD and BOR conditions. In particular, the pile was tested on June 2014 and February 2015 at EOD and BOR conditions, respectively. BOR tests were conducted in three phases, periodically up to 9 months during pile installation, including 21 hours, 9 days, and 263 days after the end of initial driving (EOD). Signal matching CAPWAP analyses were performed on the raw PDA data to determine the variation of pile capacity with depth and time. Similar to the results reported in the literature [1], Figure 3 illustrates that the variation of shaft capacity is more pronounced than that of end bearing as the time elapses. This implies that set-up is generally associated with the shaft length and has significant effect on skin friction.

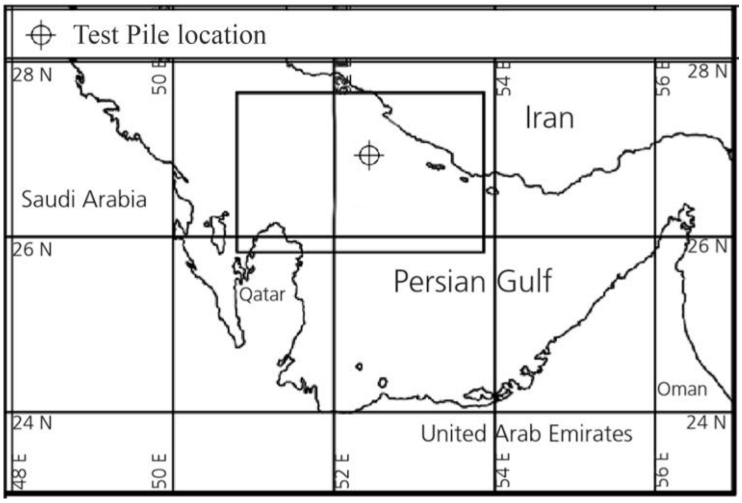

**Figure 1. Test Pile location in South Pars field, Persian Gulf, Iran**

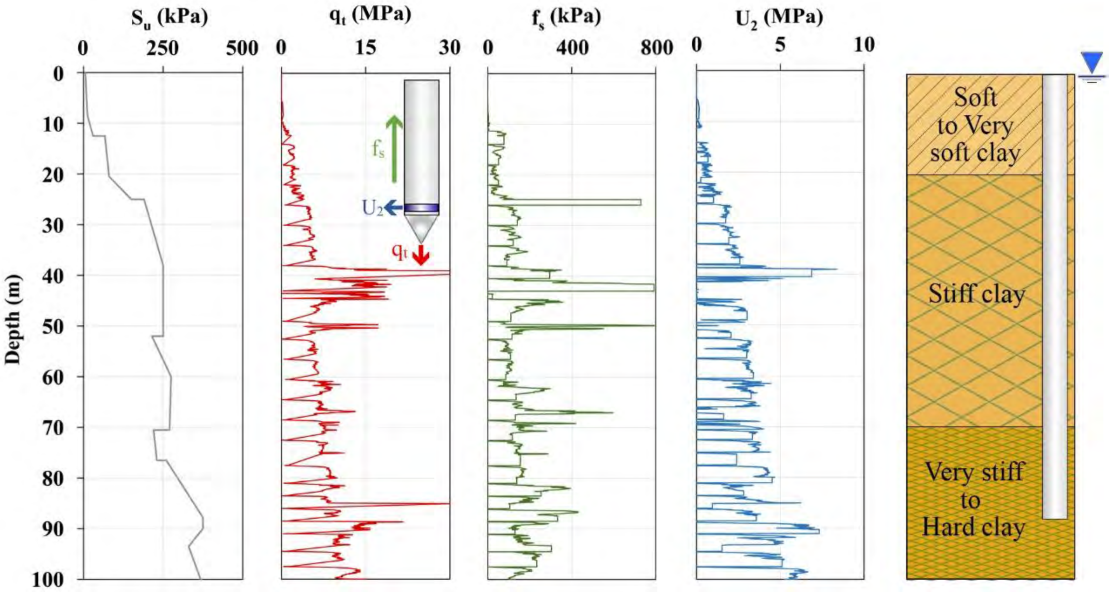

Figure 2. Soil profile and field and laboratory results at the location of test pile [1]

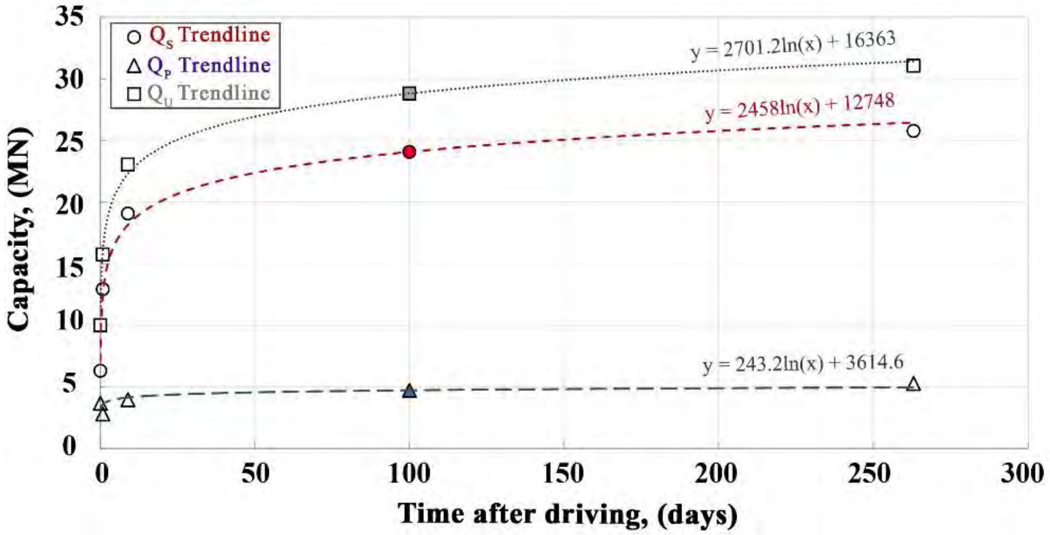

Figure 3. Varaiation of skin friction, end and ultimate bearing capacities versus time for the test pile

## 3. PILE BEARING CAPACITY PREDICTION

Numerous direct CPT based methods are available for predicting pile capacity. Herein, the direct CPT and CPTu methods employed to evaluate the test pile capacity are Penpile method (Clisby et al., 1975) [13], Shmertmann method (Shmertmann & Nottingham, 1978, 1975) [8], Aoki & Velloso method (Aoki & de Alencar Velloso, 1975) [14], European methode (de Ruiter & Beringen, Dutch method, 1979) [9], Cone-m method (Tumay & Fakhroo, 1981) [11], LCPC method (Bustamanate & Gianeseli, LCP method, 1982) [10], Price & Wardle method (Price & Wardle, 1982) [12], Unicone Method (Eslami and Fellenius, 1997) [7], and Enhanced Unicone method (Niazi & Mayne, 2015) [6]. The static analysis methods used to determine the pile capacity are API (American Petroleum Institute, 2007) [1], ICP (Jardine et al., 2005) [5], FBV (Kolk & van der velde, Fugro method, 1996) [3] and NGI (Karlsrud et al., 1999) [4]. According to the literature, the time delay between initial pile driving and the loading tests has not been applied in CPT and CPTu based methods. However, it has been taken into account for some methods including UWA (2 to 68 days), NGI (100 days), ICP (50 days), and FBV (30 days).

The predicted skin friction, end and ultimate bearing capacities obtained from various methods using CPTu data are presented in Table 1 and Figure 4. The results demonstrate a very wide range of variation in the predicted capacities. Over a period of 9 months, Tables 2-4 clearly indicate the ratio of predicted to measured bearing capacities ($Q_{(predicted)}$ / $Q_{(measured)}$) for skin friction, end bearing and ultimate ones, respectively. As illustrated, this ratio is calculated at four different times; immediately, 21 hours, 9 days and 263 days after initial driving, corresponded to End-Of-Driving, Short-, Medium- and Long-Term conditions, respectively.

**Table 1. Predicted skin friction ($Q_S$), end bearing ($Q_P$), and ultimate bearing capacity ($Q_U$) obtained from various methods**

| NO. | Depth (m) | Method | Type | $Q_S$ (MN) | $Q_P$ (MN) | $Q_U$ (MN) |
|---|---|---|---|---|---|---|
| 1 | 88 | API [2] | Static | 56.79 | 6.12 | 62.91 |
| 2 | 88 | FBV [3] | Static | 47.65 | 6.12 | 53.78 |
| 3 | 88 | NGI [4] | Static | 50.44 | 6.12 | 56.57 |
| 4 | 88 | ICP [5] | Static | 29.44 | 6.57 | 36.01 |
| 5 | 88 | Enhanced Unicone [6] | CPTu | 39.29 | 6.80 | 46.08 |
| 6 | 88 | Unicone [7] | CPTu | 24.40 | 8.13 | 32.53 |
| 7 | 88 | Shmertmann [8] | CPT | 16.05 | 9.21 | 25.26 |
| 8 | 88 | European [9] | CPT | 36.60 | 4.22 | 40.82 |
| 9 | 88 | LCPC [10] | CPT | 11.54 | 7.42 | 18.96 |
| 10 | 88 | Cone-m [11] | CPT | 20.91 | 9.21 | 30.12 |
| 11 | 88 | Price & Wardle [12] | CPT | 23.91 | 2.95 | 26.86 |
| 12 | 88 | Penpile [13] | CPT | 13.07 | 2.11 | 15.18 |
| 13 | 88 | Aoki & Velloso [14] | CPT | 47.19 | 4.82 | 52.01 |

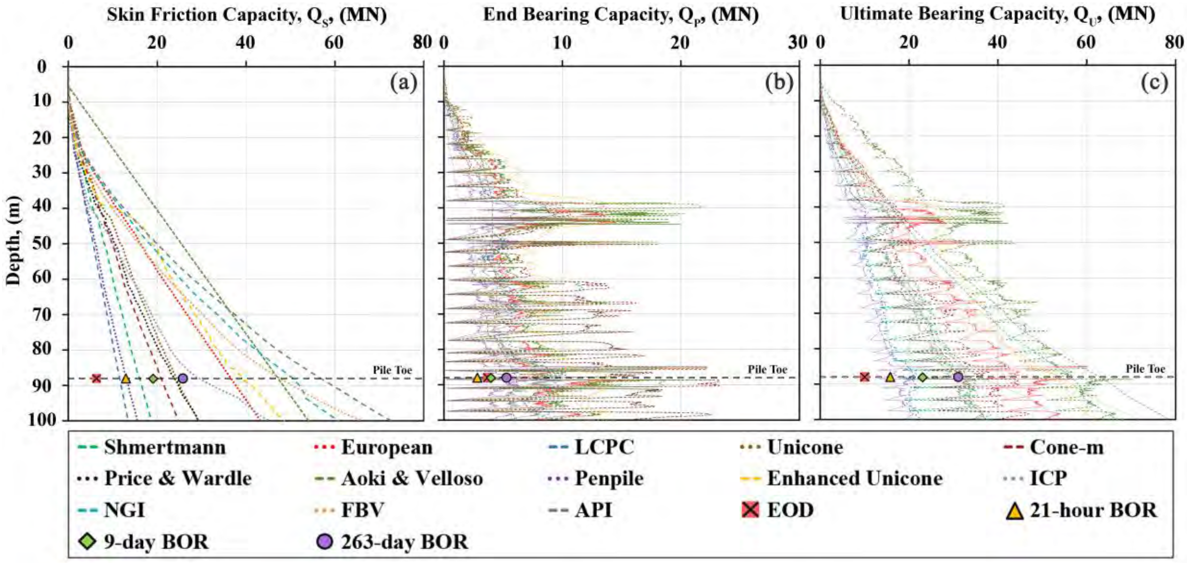

**Figure 4. Axial compression capacity curves obtained from different methods and PDA results for: a) skin friction, b) end bearing, and c) ultimate capacity**

## 4. TIME FUNCTION

Herein, the existing empirical relations of time function proposed by Skov and Denver (1988) [15], Bullock et al. (2005) [17], and Clausen and Aas (2000) [18] have been assessed and it is attempted to introduce an alternative time function based on pile test data. A well-known relationship between time after initial pile installation (t) and axial pile capacity (Q) is described by Skov and Denver (1988) [15] and expressed as:

$$Q = Q_0 \{1 + \Delta_{10} \log_{10}(\frac{t}{t_0})\} \tag{1}$$

where, Q is the vertical bearing capacity at time t at the end of installation; $Q_0$ is the reference capacity determined based on the reference time ($t_0$); and $\Delta_{10}$ is a factor providing the capacity increase corresponding to a ten-fold increase in time. In the following, $\Delta_{10}$ is referred to as the set-up factor.

**Table 2. Predicted ($Q_p$) against measured ($Q_m$) skin friction capacities, $Q_{S\text{ (predicted)}} / Q_{S\text{ (measured)}}$, during time period**

| Method | End-Of-Driving | Short-Term | Medium-Term | Long-Term |
|---|---|---|---|---|
| | $Q_p / Q_{m\text{ (EOD)}}$ | $Q_p / Q_{m\text{ (21-hour BOR)}}$ | $Q_p / Q_{m\text{ (9-day BOR)}}$ | $Q_p / Q_{m\text{ (263-day BOR)}}$ |
| API | 8.98 | 4.39 | 2.98 | 2.20 |
| FBV | 7.54 | 3.68 | 2.50 | 1.85 |
| NGI | 7.98 | 3.90 | 2.65 | 1.96 |
| ICP | 4.66 | 2.28 | 1.55 | 1.14 |
| Enhanced Unicone | 6.22 | 3.04 | 2.068 | 1.52 |
| Unicone | 3.86 | 1.89 | 1.28 | **0.96** ✓ |
| Shmertmann | 2.54 | 1.24 | 0.84 | 0.62 |
| European | 5.79 | 2.83 | 1.92 | 1.42 |
| LCPC | 1.83 | 0.89 | 0.61 | 0.45 |
| Cone-m | 3.31 | 1.62 | **1.10** ✓ | 0.81 |
| Price & Wardle | 3.78 | 1.85 | 1.25 | **0.93** ✓ |
| Penpile | 2.07 | **1.01** ✓ | 0.69 | 0.51 |
| Aoki & Velloso | 7.47 | 3.65 | 2.47 | 1.83 |

**Table 3. Predicted ($Q_p$) against measured ($Q_m$) end bearing capacities, $Q_{P\text{ (predicted)}} / Q_{P\text{ (measured)}}$, during time period**

| Method | End-Of-Driving | Short-Term | Medium-Term | Long-Term |
|---|---|---|---|---|
| | $Q_p / Q_{m\text{ (EOD)}}$ | $Q_p / Q_{m\text{ (21-hour BOR)}}$ | $Q_p / Q_{m\text{ (9-day BOR)}}$ | $Q_p / Q_{m\text{ (263-day BOR)}}$ |
| API | 1.66 | 2.18 | 1.54 | 1.16 |
| FBV | 1.66 | 2.18 | 1.54 | 1.16 |
| NGI | 1.66 | 2.18 | 1.54 | 1.16 |
| ICP | 1.78 | 2.33 | 1.65 | 1.24 |
| Enhanced Unicone | 1.84 | 2.41 | 1.71 | 1.29 |
| Unicone | 2.21 | 2.89 | 2.05 | 1.54 |
| Shmertmann | 2.50 | 3.27 | 2.32 | 1.74 |
| European | 1.14 | 1.50 | **1.06** ✓ | 0.80 |
| LCPC | 2.01 | 2.64 | 1.87 | 1.41 |
| Cone-m | 2.50 | 3.27 | 2.32 | 1.74 |
| Price & Wardle | 0.80 | **1.05** ✓ | 0.74 | 0.56 |
| Penpile | 0.57 | 0.75 | 0.53 | 0.40 |
| Aoki & Velloso | 1.31 | 1.71 | 1.21 | **0.91** ✓ |

**Table 4. Predicted ($Q_p$) against measured ($Q_m$) ultimate bearing capacities, $Q_{U\text{ (predicted)}} / Q_{U\text{ (measured)}}$, during time period**

| Method | End-Of-Driving | Short-Term | Medium-Term | Long-Term |
|---|---|---|---|---|
| | $Q_p / Q_{m\text{ (EOD)}}$ | $Q_p / Q_{m\text{ (21-hour BOR)}}$ | $Q_p / Q_{m\text{ (9-day BOR)}}$ | $Q_p / Q_{m\text{ (263-day BOR)}}$ |
| API | 6.29 | 3.99 | 2.73 | 2.03 |
| FBV | 5.379 | 3.41 | 2.33 | 1.73 |
| NGI | 5.659 | 3.59 | 2.45 | 1.82 |
| ICP | 3.60 | 2.29 | 1.56 | 1.16 |
| Enhanced Unicone | 4.61 | 2.93 | 2.00 | 1.48 |
| Unicone | 3.259 | 2.07 | 1.41 | **1.05** ✓ |
| Shmertmann | 2.52 | 1.60 | **1.10** ✓ | 0.81 |
| European | 4.08 | 2.59 | 1.77 | 1.31 |
| LCPC | 1.90 | 1.20 | 0.82 | 0.61 |
| Cone-m | 3.01 | 1.91 | 1.31 | **0.97** ✓ |
| Price & Wardle | 2.68 | 1.71 | 1.17 | 0.86 |
| Penpile | 1.51 | **0.96** ✓ | 0.66 | 0.49 |
| Aoki & Velloso | 5.20 | 3.30 | 2.26 | 1.67 |

In this paper, the attention has been paid to the form and magnitude of $\Delta_{10}$. A relation between t and Q as expressed in Equation (1) denotes a time function. According to Skov and Denver (1988) [15], the values of $\Delta_{10}$ in Equation (1) for piles driven in sand, clay and chalk are 0.2, 0.6 and 5.0, respectively. Correspondingly, the reference time ($t_0$) is assumed to be 0.5, 1.0 and 5.0 days. Attar (2013) [16] proposed $\Delta_{10}$ factor of 0.5 and $t_0$ of 1 day for the dominant clayey site on the basis of 14 test pile results at different times from initial driving. Bullock et al. (2005) [17] suggested using $\Delta_{10} = 0.1$ and $t_0 = 1$ day for design purposes if predictor tests have not been performed, and higher values when supported by dynamic and static tests. Augustesen et al. (2006) [19] recommended the values of 0.24 for $\Delta_{10}$ and 100 days for $t_0$ in clayey soil conditions based on 18 cases including 27 piles and in total 88 loading tests and also, time elapses varied from 22 to 9778 days after the end of driving. Doherty and Gavin (2013) [20] suggested the setup coefficient of 0.26 and also reference time of 100 days for the Belfast harbor tests.

Augustesen et al. (2005) [21] expressed $\Delta_{10}$ as follows:

$$\Delta_{10} = 1.24 - (\frac{S_{uu}}{S_{uu}^{0}})^{0.03} \tag{2a}$$

$$S_{uu}^{0} = 60\ kPa \tag{2b}$$

where, $S_{uu}$ is the average unconsolidated undrained shear strength in kPa along the pile shaft. By introducing a reference strength ($S_{uu}^{0} = 60\ kPa$), $\Delta_{10}$ becomes dimensionless. Again, the reference time ($t_0$) is chosen to be 100 days. For the $S_{uu}$ range examined, $\Delta_{10}$ varies between 0.22 and 0.29. Based on the test pile data, the average unconsolidated undrained shear strength, $(S_{uu})_{avg}$, along the pile shaft is around 196.70 kPa; therefore, $\Delta_{10}$ will be 0.22.

Considering the scatter and the power of 0.03, Augustesen et al. (2006) [19] concluded that there is no "distinctive" correlation between $S_{uu}$ and the set-up factor. Additionally, Clausen and Aas (2000) [18], postulate that the long-term set-up depends on the soil properties. Thus, $\Delta_{10}$ is a function of plasticity index ($I_p$) and the over-consolidation ratio (OCR), as follows:

Equation (3) has been developed by the Norwegian Geotechnical Institute (NGI). In the relations, the plasticity index ($I_P$) and over-consolidation ratio (OCR) are average values along the pile shaft.

$$\Delta_{10} = 0.1 + 0.4(1 - \frac{I_P}{50})OCR^{-0.8} \tag{3a}$$

$$0.1 \leq \Delta_{10} \leq 0.5 \tag{3b}$$

According to test pile data, $(I_P)_{avg}$, and $(OCR)_{avg}$ are 28.65 and 1.51, respectively. As a result, $\Delta_{10}$ is equal to 0.22.

Augustesen et al. (2006) [19] proposed that the time function presented by Skov and Denver (1988) [15] provides the most suitable fit against the available data whereas the model suggested by Clausen and Aas (2000) [18] provides the least suitable fit in spite of the fact that Clausen and Aas (2000) [18] relation includes a dependency on soil properties. So, when estimating the long-term capacity in the test pile location in Persian Gulf, it is recommended to use the time function based on Skov and Denver (1988) [15] and Clausen and Aas (2000) [18] equations with reference time of 100 days.

Considering the calculated ratios of different methods which has been presented in Tables 2-4, Figure 6 illustrates the best results that falls within the range between 0.90 and 1.10. Given the fact that the closest results to 1 are the most desirable ones, current study demonstrates the best estimations related to skin friction, end and ultimate bearing capacities in long-term condition.

## 9. CONCLUSIONS

This paper compares the results of 13 popular methods used to determine the axial bearing capacity of an open steel pipe pile against the PDA data recorded in the south Pars field, Persian Gulf, Iran. The methods include seven CPT based methods, two CPTu based methods and four static analysis methods. The calculated skin friction, end and ultimate bearing capacities of pile using these predictive methods were compared to the measured values. In this regard, the ratio of predicted to measured resistances, ($Q_p/Q_m$), has been used to evaluate the prediction quality and appropriateness of the given methods.

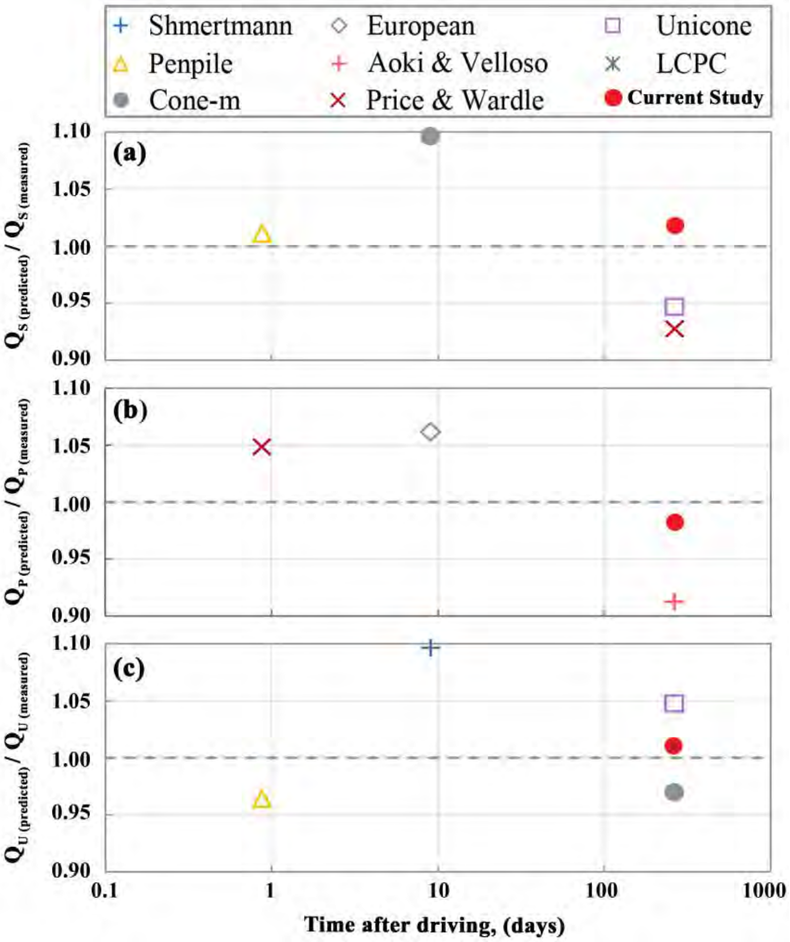

**Figure 5. The ratio of predicted to measured resistances, ($Q_p/Q_m$) in a range between 0.90 and 1.10 for: a) skin friction, b) end bearing and c) ultimate capacities**

**Table 5. Set-up models of different methods based on Skove and Denver (1988) equation [15]**

| Model | $\Delta_{10}$ | $t_0$ | t | Eq (1) / $Q_{m\,(S\text{-}263\text{ day BOR})}$ | Eq (1) / $Q_{m\,(P\text{-}263\text{ day BOR})}$ | Eq (1) / $Q_{m\,(U\text{-}263\text{ day BOR})}$ |
|---|---|---|---|---|---|---|
| | (-) | (day) | (day) | | | |
| Skov and Denver (1988) | 0.6 | 1 | 263 | 1.21 | 1.68 | 1.29 |
| Attar (2013) | 0.5 | 1 | 263 | 1.06 | 1.51 | 1.16 |
| Bullock et al. (2005) | 0.1 | 1 | 263 | 0.61 | 0.85 | 0.64 |
| Augustesen et al. (2005) | 0.22 | 100 | 263 | 1.02 | 0.99 | 1.01 |
| Augustesen et al. (2006) | 0.24 | 100 | 263 | 1.03 | 0.99 | 1.02 |
| Doherty and Gavin (2013) | 0.26 | 100 | 263 | 1.04 | 0.99 | 1.03 |
| Clausen and Aas (2000) | 0.22 | 100 | 263 | 1.02 | 0.99 | 1.01 |

According to the calculated results of 13 methods, the Unicone method (1997) [7] exhibits the highest level of appropriateness in long term condition. In contrast, the API method (2007) [2] shows the lowest level of certainty in predicting pile capacity after 263 days of initial driving.

Additionally, considering the set-up models proposed in the literature, the time function proposed by Skov and Denver (1988) [15] provided the best results in comparison with the available data. The set-up factor ($\Delta_{10}$) proposed by Bullock et al. (2005) [17], Attar (2013) [16], Doherty and Gavin (2013) [20] and Skov and Denver (1988) [15] employ a constant value of set-up factor and also over-predicts the capacity at long-term condition. However, in Clausen and Aas (2000) [18] equation, $\Delta_{10}$ depends on the properties of soil which results in the most appropriate set-up factor.

Finally, this study suggests using the time function based on the Skov and Denver (1988) equation and the set-up factor based on the Clausen and Aas (2000) [18] equation with reference time of 100 days.

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